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LÁSZLÓ JAKUCS

PREFACE

This special issue of Acta Geographica is dedicated to **Professor László Jakucs**, the well-known researcher of the karst, on the occasion of his 70th birthday. László Jakucs is the member of the generation of karst researchers that following H. Lehmann, made significant contributions and achieved important scientific results in interpreting the combined karst phenomena. He has been and still is doing versatile research on the surface and subsurface karst genetics. He has discovered several caves and his career can be set as an example for young generations of karst researchers to follow.

László Jakucs was born on 21st January 1926 at Sarkad. His father was a teacher in a country school and taught his son the love of nature and scientific reasoning. He went to secondary school in Debrecen. He was influenced by the work of András Hoffer, a geologist who took him on geologic surveys several times. He was especially interested in mineralogy first. He had a considerable collection of minerals that he had given to the Institute of Mineralogy and Geology in Debrecen later on.

He started his university studies at the Department for Physical Geography and Chemistry in Budapest. Then he specialized in Geology, under the guidance of Elemér Vadász. From 1947 he became a research student at the Geologic Institute of the university and he graduated as a geologist in 1949.

While he was a university student, he surveyed and mapped the cave at Sátorkőpuszta in 1946, and he studied the genetics and morphology of the hydrothermal karst phenomena of the Buda Hills. He published his results in the Természettudomány (Natural Science), Hidrológiai Közlöny (Hydrological Bulletin) and Földtani Közlöny (Geological Bulletin). In 1949 he worked for the Hungarian National Geological Survey, where he was given a one year scholarship at the Geological Research Institute in Moscow. During this year he worked with professors Avchinjicov and Kamjanski on geohydrological and karst morphological projects.

From 1950 he did researches on the karst water system of the Bükk Mountains, applying water colouring methods. In doing so he discovered and surveyed the so far unknown Létrás sink-hole cave.

From 1952 he started working in the Aggtelek Karst Region. Using new methods of research he calculated the location of several, so far unknown caves, among which the 10 km long Béke Cave was the largest. He discovered it in August 1952, and then mapped the cave. When surveying the genetics of the cave system, he proved it to be the product of the erosion of solid sediments transported by the seasonally flooding streamwaters arriving from non-karst areas instead of the product of solvent corrosion.

Besides his scientific researches he made significant contribution to the development of domestic karst research. In 1951 he organized the Karst and Speleology Research Section of the Hungarian Geographic Society. His studies and books published at that time did a great job in making speleology almost a popular movement. In 1953 he and his colleagues discovered and surveyed the Pénzpatak Cave System in the Bükk Mountains.

From 1953 he had been the director of the Aggtelek Dripstone Cave for 10 years. He was engaged in developing the region of the cave and in the scientific surveying of the region itself.

During this time his monography written on Aggtelek and a film entitled Aggtelek were issued. This latter won the 'World's best cave film' title and cup on the 2nd International Speleological Congress in Italy in 1958. Several films were made on his results in karst research, like a Hungarian TV film on the discovery of Béke Cave, and a German film entitled 'Mit Höhlenforschern in Nordungarn II. Lokaltermin nach 36 yahren'.

In 1963 he was appointed assistant professor at the Szeged University, where in 1964 he organized the Department of Physical Geography, which he had been heading for 28 years.

As a university lecturer he organized several research journeys abroad. The most successful ones took place in the karst regions of Yugoslavia, the Krim Peninsula, Podolia, the Alps and Cuba. In 1971 he organized a regional IGU conference entitled 'Karstmorphological Symposium'.

His scientific activity transformed the traditional views on karst morphology. He separated two large groups of limestone karsts. Type 'A', the autogenic one where karst phenomena and morphology are formed through corrosional processes and type 'B', the allogenic karst, the morphology of which is being formed by alluvial erosion. He was the first in an international aspect to establish the erosional model of cave morphogenetics. He developed new principles and methods to discover unknown caves. He proved the biogenic dominance in karst processes. His new views led him to oppose the French School of J. Corbel. In his opinion the role of carbon-dioxide absorbed in precipitation from the atmosphere, is negligible in karst corrosion, because most of the carbon-dioxide content of the water comes from the soil layer covering the karst surface, thus increasing the solvent action of water.

His most important piece of work, the book entitled 'The morphogenetics of the Karst', being published in English too, can be found in every library belonging to karst research workshops all over the world.

László Jakucs worked in other fields of geomorphology as well. He examined the craters of cosmic origin on Earth's surface. He was among the firsts to interpret satellite images of Hungary from the viewpoint of hydrocarbon research in the mid 70s. He constructed the geological and paleogeographical model of a Hungarian crude oil holding structure. He analyzed the changes of water regime of the rivers in the Great Plain that were due to the effects of human activity.

As a university professor he took part in scientific life home and abroad alike. For decades he had been a member of the Meteorological Professional Committee, the Scientific Qualification and the Geographical Committees of the Hungarian Academy of Sciences. He contributed to the work of the Committee on Environmental Change of Karst Areas and the National Committee of IGU. He is the co-chairman and a honorary member of the Hungarian Karst and Speleological Society, the Hungarian Geographical Society, the Szeged Section of the Hungarian Geographical Society and the Szeged Section of the Association for Spreading Scientific Knowledge.

His life-work can be described by more than a dozen scientific books, numerous text books and almost 100 scientific articles.

He is the founder of the Szeged karstmorphological school. Many of his students are now qualified researchers at the Hungarian Academy.

His work in scientific research and education is acknowledged by several awards. He was awarded the medals of Otto Herman, Lajos Lóczy and Sámuel Teleki; the title 'Excellent Worker of Higher Education' and the golden grade of Labour Merit. In 1993, when he retired, he was given the title 'Professor Emeritus' for his several decade long, excellent activity in education.

He is an outstanding lecturer today, and still doing research. His main scientific theses are described below:

Since the carbonate-dissolving potential of water in contact with a rock varies directly as its carbonic acidity, the most important thing to establish in interpreting the corrosion dynamism is the set of conditions controlling the absorption of CO_2 and its concentration in the water. Of these conditions, the abundance of CO^2 in the soil gas entering into contact with the water turns out to be the most important: infiltrating waters derived from precipitation, which by their dissolution of limestone essentially control the entire karst evolution, gain their carbon dioxide content (determining the dynamism of corrosion) almost everywhere and always in the top horizons of the soil.

The gas composition of the soil atmosphere reacts rapidly and sensitively to both macro- and microclimatic influences; it tends to exhibit significant differences even within one and the same test site (e.g. within one doline) depending on the type of plant cover supported by the soil, and even on the individual plant species making up the rhizosphere. That is, the rate of karst evolution by corrosion is determined not only by the abundance of precipitation, but primarily by the biological features and other processes of evolution of the soil mantles of varying thickness covering the rock.

Natural karst corrosion of limestone rocks over most of the earth's land area is simply the formal imprint upon the soluble parent rock of the phenomena of biological and chemical evolution of the soil covering the rock.

Under a cold climate, the calcium carbonate carried in solution and suspension in the streams issuing from karst areas is nearly equal to the amount removed by corrosion. The non-aqueous content of the infiltrating precipitation is controlled by the influence of the soil atmosphere and its enriched CO_2 content (that is, the warmer the climate), however, the volume of precipitation influences the difference between the quantities of dissolved and removed material. This may reach the degree, largely typical of today's tropics, where the calcium carbonate removed in the streams is practically insignificant compared with the high-intensity erosion by karst corrosion.

Owing to the near-equality of the rates of corrosion and calcium carbonate removal in solution, cold-climate karsts develop into leached "skeletal karsts", whereas in a tropical karst the dissolved calcium carbonate is precipitated in the deeper horizons or almost at the site of dissolution, which turns these karsts into compact, massive ones. In these regions, calcium carbonate transportation is largely vertical, and inasmuch as if it is horizontal it is confined to a highly localized small domain.

Karsts of the temperate zones are intermediate between tropical and polar karsts not only in geographic latitude, but also morphogenetically, in the intensity and quality of products of the processes of karst corrosion.

Carbon dioxide of atmospheric origin does not play an important role in karst corrosion except in high mountains, periglacial regions and desert. In the tropical regions it is negligible in comparison with the other factors of karst corrosion. (In the tropics, for example, the biogenic CO_2 is about 100 times more effective than the atmospheric!)

The dominant feature of karst corrosion is the temperate and Mediterranean zones is a marked seasonal control of the nature and dynamism of the processes. It seems probable that the landform-controlling role of microclimatic factors is most efficient in the temperate zone. Owing to the climatic extremes typical of this zone, to the frequent alternation of freeze and thaw in the winter, producing large amounts of rubble lending considerable erosional efficiency to stream action, and to the frequent vehement floods outside the season of vegetation (in the Mediterranean zone), the formation of scour caverns is most intense in this zone of the earth's surface.

Within any given microspace, the corrosive karst process in invariably determined by the microclimatological parameters prevailing, and these of course do not depend only on the macroclimate of the area. The process of karst erosion in a region, then, should be interpreted as a statistic resultant of episodes of erosion in a mosaic of microspaces not necessarily similar in behaviour.

Depending on whether or not the drainage network of a karst carries waters flowing in from alien non-karstic areas, it is necessary to distinguish B-type (allogenic) and A-type (authogenic) karsts. In the hydrography of an authogenic karst, only the precipitation seeping in through the karst surface is available as a fundamental genetic factor, whereas in an allogenic karst linear streams of non-karstic surfaces also contribute to erosion.

In nature, only the authogenic hydrological character may appear as a pure type, the geomorphological facies of an allogenic karst invariably exhibiting hydrological and formal features of the A-type in addition to the B-type ones.

B-type (allogenic) karst erosion is simply the manifestation, with a number of special features, of a non-karstic process of relief sculpture, normal linear erosion, in the depth of the karst. Hence, the cave is not a product of dissolution, but is a simple erosion streambed under the surface. The presence or otherwise of this process in a karst region is purely accidental, depending primarily on the relationship of the karst to its non-karstic environment, and it is not an inevitable stage in the evolution of any karst. The classical interpretation of karstification as the corrosive erosion of limestone did not take into account the possible manifestation of this influence of the environment, nor its morphogenetic consequences, but considered authogenic karstification solely. This is one of the reasons why the classical definition of the karst concept must be assessed as too narrow, and unsuited for the interpretation of the full range of phenomena, since by strictly adhering to this viewpoint it would be necessary to exclude from the karst concept the largest-scale and most majestic cavern formations encountered in the karst depths throughout the world.

In the first stage of evolution of an allogenic karst, streams penetrating the area from the non-karstic surroundings continue to incise valleys by linear erosion of the karst surface. Subsequently, once the three-dimensional system of water passages in the karst has developed, the surface valleys are tapped from below by underground passages (bathycapture), and from then on the linear valley sculpture by the stream is displaced underground, where it contributes to cavern sculpture.

The conspicuous presence of aligned dolines on a karst surface may indicate that the karst in question was more or less covered and confined at he beginning of its erosional process; the traces of the dolines usually follow the traces of former stream valleys caused by linear erosion, epigenetically inherited from the time when the karst was still buried.

Structural preformation, if any, has determined the alignment only is so far as it controlled the drainage pattern in the non-karstic formation originally covering the karst mass.

Aligned dolines are invariably older and deeper-lying than individual dolines, and they are usually larger and better developed.

Retreating underground evolution in the karst under a limestone valley carrying an allogenic stream may lead to repeated, retreating episodes of bathycapture. The process keeps on repeating itself until the youngest swallow-hole attains the limit of the karstic rock mass. Thereafter, retreating erosion reaching out to the surface from the deeper-lying cavern cuts down the non-karstic surface adjacent to the karst mass, resulting in time in its insular emergence as an island.

Degradation resulting in the barrenness of the karst completely changes the set of forms of lapies fields. According to our observations, the phenomenon is so regular that this "lapies metamorphosis" in itself permits a fair estimate of the duration of degradation.

The drippings of water in caverns of a comparatively uniform yield all the year round invariably underlie forest-covered surfaces, whereas the stalactites whose yields fluctuate markedly underlie barren areas almost without exception. Another feature closely related to changes in the plant cover above caverns is the colour of dripstones. Degradation is usually accompanied by a considerable enrichment of clayey material in the dripstones and in the cavern deposit.

15th November 1995, Szeged

KARSTRESEARCH
- a traditional science involving recent applied tasks

Homage to Prof. JAKUCS
The famous Hungarian Karst scientist
who introduced applied karst research in his department

Karl-Heinz PFEFFER

1. PREFACE

During the last 150 years, the research done concerning karst phenomena and central questions changed tremendously.

First, karst research was primarily done at Universities with the main emphasis on basic research. Due to the change in responsibility from Universities to engineering offices, regional planning agencies and federal environmental conservation agencies, it is now becoming more important to apply basic knowledge. As a consequence, problems concerning ecology and environmental conservation are solved by referring on classical basic research. Obviously, this change in responsibility reveals in research and teaching. It is also well displayed in (Master) theses and publications (EK 1985, GAMS et al. 1987, PFEFFER 1990, JULIAN 1992, WILLIAMS 1993).

2. THE SITUATION OF KARST RESEARCH IN ITS BEGINNING

The systematical scientific reconnaissance, specification and explanation of natural phenomena started during the last century. In the middle of the last century, the efforts made eventually became part of several textbooks. These textbooks are considered to be the foundation for present physical geography and, especially, of present geomorphology (NAUMANN 1854, PESCHL 1869, RICHTHOFEN 1886, MAUL 1938, LOUIS & FISCHER 1979). Geographers and geologists spent much attention to the natural phenomenon that is now known as KARST. This was because of its specific landforms within certain lithofacies and its uncommon subterranean drainage combined with cave-systems. In addition, since the antiquity hydrogeological knowledge has been existed (PFEIFFER 1963). In karst regions, hydraulic engineering was used to construct buildings which are supposed to be evidences of early "applied science" (BALLIF 1896, ZÖTL 1974, JAKUCS 1977, NICOD 1972).

Hydraulic engineering was used to control the water economy of karst springs and the seasonal or partly constant inundation of poljes (DENK 1974). As early as the 1st century AD efforts, were made in the Conca di Fucino in Italy (HASSERT 1897), followed by the drainage of the polje of Cuges in the 15th century (BOUZAT 1969). As a matter of fact, the long experience over centuries in hydraulic engineering and the technical facilities of the industrial age enabled the quite successful drainage of the Lake of Fucino from 1854-1875 (HASSERT 1897), of the Kopai depression in Greece from 1883 until 1892 (PHILIPSON 1894) and of the dalmatian poljes (BALLIF 1896).

Due to some lack in basic knowledge about karst hydrology, however, man's impact in karst hydrology sometimes was - and still is - rather unsuccessful (BALLIF 1896, NICOD 1972, ZÖTL 1974, JAKUCS 1977, GAMS et al. 1987). Despite of the recent profound knowledge in karst hydrology (DREYBRODT 1988, FORD & WILLIAMS 1989), spectacular ruins are still the result in some cases of application (ZÖTL 1974, JAKUCS 1977, GAMS et al. 1987).

3. Basics and vocabulary of the self-establishing science

As always when a new science is established, the first step was to create a technical terminology defining typical features and phenomena. The publications of CVIJIC (1895, 1918) and GRUND (1914) along with the textbook of Albrecht PENCK (1904) are probably the most important acts referring to karst morphology. However, opposite views about karst hydrology, processes and dynamics of subterranean drainage and cave genesis were subject of a debate carried on with scientific keenness (PFEIFFER 1963, ZÖTL 1974, BÖGLI 1978). This debate had its first conclusion with the publication of "Hydrographie des Karstes" (O. LEHMANN 1932).

The weakness of this first period is obvious and still is acting as an impediment to the correct use of the nomenclature. This is because karst features were named only by the karst regions being located in the margins of Vienna University. Especially the slovenian region "Kras" was serving as the model landscape that, among other things, provided the term "karst."

Yet little was known about other karst landscapes differing from the model landscape. At the beginning of this century, certain travel notes informed about differing karst regions, eg like in Java or Jamaica (DANES 1908, 1910). Information which was taken from these notes was included in the schools of this time. This was sometimes resulting in rather wrong designations like, for example, by GRUND 1914, who called the karst cones "cockpits." Moreover, the transfer of terms originating from the dinaric area to regions showing totally different landforms and a different history, was not really useful for further research.

During this first phase, GRUND (1914), CVIJIC (1924), SAWICKI (1909), SANDERS (1921) tried to explain karst phenomena in a geomorphological way with models derived from the cycle of William Morris DAVIS (1912). Despite of the progress made after the second World War, several publications of this time still referred to these models as valid ideas of karst genesis (CORBEL 1959, STRAHLER 1969, SMALL 1972). During this first period, studies on hydrological karst processes (KATZER 1909, O. LEHMANN 1932) were carried out without the help of modern tracer and automatic measuring techniques, and also without hydraulic 3-dimensional computer-assisted simulation analysis and modelling. Therefore, ideas of this time are quite incomplete in comparison to recent studies (BUHMANN & DREYBRODT 1985, 1985a, DREYBRODT 1988, FORD & WILLIAMS 1989, WHITE 1988).

4. KARST RESEARCH FOCUSED ON CLIMATIC GENETIC PROCESSES

During the 1930's and the second World War, the economical and political circumstances prevented scientific progress. It was not earlier than in the 1950's, that a new era in karst research evolved due to the international cooperation within the scope of the International Geographic Union (IGU). The rise of modern facilities in travelling and the access to aerial photographs and maps of areas formerly difficult to survey, was followed by a multitude of regional publications. With the protectorate of the IGU, Herbert LEHMANN gave the impulse to create an international atlas of karst phenomena (LEHMANN & MORANDINI 1960).

In its original conception, it should represent selected karst landscapes by topographic maps, plates and text pages. Because of the almost boundless availability of topographic maps, aerial photographs and the multitude of regional publications at this time, however, the original conception became antiquated with the appearance of sheet No.3 (GERSTENHAUER 1964). It was not until the 1980's that, with the protectorate of the Union of International Speleology (UIS), the work on this atlas continued having the following outline. Karst regions are represented by maps which were created by many contributors applying their own specific geomorphological and geoecological mapping methods. Each map is illustrated by detailed text portions (PFEFFER 1986a, 1990a).

International publications, meetings and symposiums gave evidence for the thesis that the different appearances of karst landscapes cannot be longer described by means of the DAVIS cycles. This statement also was already made by LEHMANN in 1936. Well-developed cockpit-karst, for example was always described as an old landscape in terms of DAVIS, but proved to be young. Moreover, in some regions cockpit-karst was sometimes developed since the Neogene, if not since the Quaternary. In contrast to this, dolines formerly dated as young as to speak again in DAVIS cycles, now were dated in the mid or older Tertiary (LEHMANN 1956, 1964, 1970, SWEETING 1972, PFEFFER 1986). Later on, the slogan "climatic genetic styles" was invented, and it was in the 1950's that a new period of research began with the observation of the karst regions of the earth in a climatic genetic context. Qualitative and quantitative sampling techniques should prove the evolution of specific styles (FUCHS, GERSTENHAUER & PFEFFER 1987).

The spatial distribution of specific karst regions and morphodynamic studies provided significant examples, like

* fluvio karst of former periglacial regions (WAGNER 1960)
* old karst landscapes showing dolines in the temperate climates (PALMER 1975)
* cockpit karst in the neogene limestones of the humid tropics (BLUME 1968, BALÁZS 1968, SWEETING 1972)

* the lack of karst hydrology in periglacial regions (CORBEL 1954, 1954a, MUIR & FORD 1985, also ZÖTL 1974, JAKUCS 1977).
* the lack of karst hydrology in arid regions showing surface flow in times of heavy rains and valley cutting (PFEFFER 1975, 1976).

In contrast, qualitative and quantitative measurements yielded contradictions and did not confirm the thesis of climatic genetic processes and landforms.

At first, this was due to the weakness of some measurement methods and the incorrect selection of measurement places (CORBEL 1959). The application of reproducible and specifically selected reliable field techniques, however, yielded values ranging within 10 times throughout the world. These variations appeared in the field of carbon dioxide analysis (MIOTKE 1974), in the field of water chemistry (BÖGLI 1978, BAUER 1962), as well as in balances based on geological time marks like Karrentischen (BÖGLI 1961, CLAYTON 1981) and standard tablets (GAMS 1979). At the same time it was observed that in the tropics as well as in the non tropics, about 50 mm carbonate is eroded in 1000 years when the floor is covered with vegetation (PRIESNITZ 1974, SWEETING 1964).

This discrepancy between the spatial distribution of karst landscapes throughout the world, the geomorphological-geological analysis and the quantitative sampling techniques has not been cleared so far (PFEFFER 1989).

As a consequence, different evaluations can be explained because of this discrepancy. The evaluations range from critical statements up to the rejection of recent carbonate erosion measurement values because of the following facts:

* ecosystems are disturbed by human impact (PFEFFER 1990, GAMS et al. 1987, WILLIAMS 1993)
* many karst landscapes would have been already eroded, if the present measurement values of carbonate dissolution were correct. Nevertheless, karst landscapes are represented by old surfaces covered with paleosoils as well as by bornhardts being sculptured in contrast to surrounding rocks (LEHMANN 1956, TROLL 1973).
* studies indicate that weathering in paleoclimates was more intense and different to present weathering processes (VALETON 1983). In addition, it was mentioned in paleoclimates morphodynamic processes were different because of different geoecological conditions (ROHDENBURG 1971).

For this reason, the application of actualism in geomorphology and morphodynamics is quite dubious.

On the other hand, statements maintain that there are indeed big differences in dissolution and erosion processes because of different climatic conditions (SALOMON & MAIRE 1992). But including all geocomponents, however, karst landscapes primarily differ because of differences in structure and lithofacies (NICOD 1982, SWEETING 1979, DAY 1979, ROSSI 1980, MONROE 1976, SALOMON 1987).

After all, hydrologists claimed that it is more a question of water balance than of climatic genetic processes how karst landscapes will develop. This was verified by model calculations being oriented on mass balances of karst landscapes. Finally, Derek FORD (lecture - Hamilton 1993) and Paul WILLIAMS (lecture Singapore 1995) stated that "tropical cockpit karst" will even develop in a non tropic climate when sufficient water supply is guaranteed. This statement still is examined (BUHMANN & DREYBRODT 1985, 1985a, DREYBRODT 1988, FORD & WILLIAMS 1989, WHITE 1988).

Further basic research concerning these discrepancies will provide more profound knowledge about the evolution of karst landscapes.

5. KARST RESEARCH AS A PART OF RESEARCH IN ECOLOGY AND ENVIRONMENT

Since even humanity is threatened because of global and regional changes in the ecological system, the relation with nature changed. In contrast to the 1960's, where sociological and economical changes had priority, ecology and environmental conservation nowadays became more important for the management of natural resources.

Even karst research was influenced by this change of mind. Despite of their small aquifers, quite many karst landscapes served as water-reservoirs and karst springs often provide water for some parts of remote urban areas. Furthermore, endangered species of fauna and flora can often be found in karst landscapes. Especially in the European Mittelgebirge, natural resources management and environmental conservation compete with traditional but meanwhile industrial farming, as well as with urban population looking for outdoor recreation (PFEFFER 1990).

Competing kinds of land use require well-devised planning. Therefore, science should try to provide the required parameters for application. In terms of karst, these parameters are, for example,

* **in engineering sciences**: studies in the hydraulics of flow dynamics within the karst system, followed by studies in the karstwater level position. Moreover, possible ways of purifying karst water should be examined.

* **in hydrology**: studies in the action of pollutants in aquatic karst systems and studies in the chemical and dynamical flow behaviour of springs resulting from processes on the karst surface, or especially in the Epikarst.

* **in geography**: the quantification and evaluation of geoecological conditions in karst landscapes, including plants and animals.

Because of the fact that this report is written by a geographer, we now will have a closer look on the latter parameters.

6. TECHNIQUES OF KARST LANDSCAPE ECOLOGY

The goal is to generate a geoecological evaluation as a foundation for environmental conservation planning and resources management. First, spatially prevailing zones must be defined with the help of certain criterions, like geomorphological landforms (karst cones, dry valleys, dolines, Karrenfelder), significant types of meadows and woods or the distribution of subsurface layers (loess, moraine, paleosoils). The combination of a couple of parameters sometimes also works.

Figure 1 shows an example for the definition of spatially prevailing zones in an area located in the karst region Hutton Roof/Cumbria in northwestern England. The parameters "subsurface layers" (limestone, loess and moraine coverage), "soils" (pavement without vegetation, rendzina soils, brown soils) and "vegetation" (pavement without vegetation, grass and fern families) served as criterions.

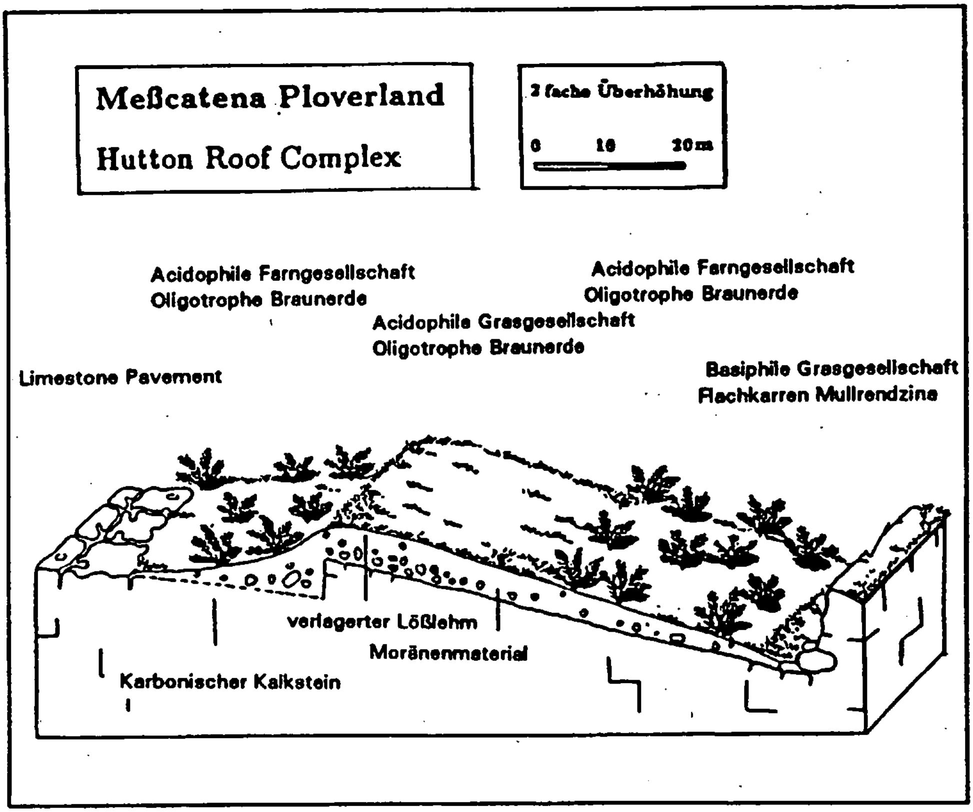


Figure 1 *The definition of spatially prevailing zones (PFEIFFER, P. 1991, Fig. 36, p. 95)*

Within such defined zones sampling places can be selected according to profiles or principles used for catenas or, the simplest way, by a "Typlokalität."

In addition, sampling places are checked by soil samples drilled with the Pürckhauer Bohrstock.

The next step is to map vegetation involving the methods described by BRAUN-BLANQUET (1964) and OBERNDORFER (1990). The identification of the growing conditions of the plants, documented in a system of "Zeigerwerte" (ELLENBERG 1991) enables the following ecological interpretation.

Table 1 shows an example and the result of such a vegetation mapping and the ecological interpretation according to "Zeigerwerten" in a "Kalkmagerrasen Ökotop" located in the Muschelkalk of southern Germany (LEIENDECKER 1992).

The subsequent excavation of a pit provides the possibility to describe the subsurface layer by geological, sedimentological, petrological and soil-scientific techniques.

Figure 2 shows an example of the documentation of a profile located in the "Kuppenalb" area of the southwestern "Schwäbischen Alb" (GOMMEL 1995).

Several layers and pedogenetic horizons serve as criterions for further analysis in a laboratory.

Soil samples are examined with the instructions given by the lab manual (BECK et al. 1994), what means that the soil is analysed by determining its grain size, acidity, exchange of cations, as well as its carbon concentration and nutritive substances. The heavy metal concentration and content of pedogenetic iron or aluminum in solution is analyzed occasionally.

Several textbooks of soil-science (ARBEITSGEMEINSCHAFT BODENKUNDE 1992, KUNTZE, ROESCHMANN & SCHWERDTFEGER 1994, REHFUSS 1990, SCHEFFER & SCHACHTSCHABEL 1989) provide the required limiting values and data for the subsequent ecological interpretation of the data gained in lab analysis. The final interpretation is done by the combination of data gathered by fieldwork and the lab data.

Figure 3 shows an example of the evaluation of a Muschelkalk slope having different vegetation located in a nature reserve in the Main-Tauber Kreis. Furthermore, it shows facts concerning the potential growth of several plants, bushes and erosion.

Objects being under natural protection or objects that eventually will become parts of a natural protection area require a special treatment. This means that mapped vegetation is compared with the Roten Liste (KORNECK & SUKOPP 1988), a list containing all sorts of endangered plants. The system created by MARKS et al. (1989) helps to evaluate how far objects must be protected.

Figure 4 shows an example of the classification of a wet meadow located in the area of the Uracher volcanism of the "Schwäbische Alb" (Ullrich 1992).

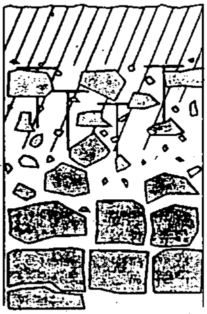
Data that has been gathered by the evaluation and analysis of sampling locations is transferred to the previously defined geoecological zones. This is done manually or with a computer using a Digital Elevation Model. A GIS provides the database and the possibility to create hard copies.

		Zeigerwerte nach ELLENBERG et al. 1991						
Wissenschaftlicher Name	**AM**	**L**	**T**	**K**	**F**	**R**	**N**	**Deutscher Name**
Strauchschicht:								
Juniperus communis	r	8	.	.	4	.	.	Gewöhnlicher Wacholder
Sorbus aria	r	6	5	2	4	7	3	Mehlbeerbaum
Cornus sanguinea	r°	7	5	4	5	7	.	Roter Hartriegel
Krautschicht:								
Anthericum ramosum	3	7	5	4	3	7	3	Ästige Graslilie
Brachypodium pinnatum	1	6	5	5	4	7	4	Fieder-Zwenke
Genista tinctoria	+	8	6	3	6~	6	1	Färber-Ginster
Centaurea scabiosa	+	7	.	3	3	8	4	Skabiosen-Flockenblume
Cirsium acaule	+	9	5	4	3	8	2	Stengellose Kratzdistel
Geranium sanguineum	+	7	6	4	3	8	3	Blut-Storchschnabel
Hieracium piloselloides	+	9	6	4	4~	8	2	Florent. Habichtskraut
Lotus corniculatus	+	7	.	3	4	7	3	Gewöhnlicher Hornklee
Scabiosa columbaria	+	8	5	2	3	8	3	Tauben-Skabiose
Stachys recta	+	7	6	4	3	9	2	Aufrechter Ziest
Teucrium chamaedrys	+	7	6	4	2	8	1	Edel-Gamander
Cornus sanguinea	r	7	5	4	5	7	.	Roter Hartriegel
Aster amellus	r	8	6	6	4	9	3	Kalk-Aster
Bupleurum falcatum	r	6	6	6	3	9	3	Sichelblättr. Hasenohr
Carlina vulgaris	r	7	5	3	4	7	3	Golddistel
Koeleria pyramidata	r	7	6	4	4	7	2	Pyram.-Kammschmiele
Echium vulgare	r	9	6	3	4	8	4	Stolzer Heinrich
Euphorbia cyparissias	r	8	.	4	3	.	3	Zypressen-Wolfsmilch
Gymnadenia conopsea	r	7	.	2	7~	8	3	Mücken-Handwurz
Hypericum perforatum	r	7	6	5	4	6	3	Echtes Johanniskraut
Peucedanum cervaria	r	7	6	4	3	7	3	Hirsch-Haarstrang
Lactuca perennis	r	9	7	4	2	8	2	Blauer Lattich
Linum tenuifolium	r	9	8	4	2	9	2	Zarter Lein
Pulsatilla vulgaris	r	7	6	5	2	7	2	Gewöhnl. Küchenschelle
Sanguisorba minor	r	7	6	5	3	8	2	Kleiner Wiesenknopf
Salvia pratensis	r	8	6	4	3	8	4	Wiesen-Salbei
Gesamtartenzahl	29							
Mittlere Zeigerwerte		7,5	5,8	3,9	3,5	7,7	2,7	
Deckungsgrad Krautschicht (%)	70							
Strauchschicht	<5							
Größe der Aufnahmefläche (m^2)	50							

Table 1 *Vegetation mapping of a "Kalkmagerrasen Ökotop" (LEIENDECKER, T. 1992, Tab.5, p.34)*

sehr stark humose Mull - Braunerde-Rendzina aus geringmächtigen Deckschichten [HL-BL?] über Weißjura-β-Zersatzzone

Lage, Oberflächenrelief	RW-3484,8 HW-5337,3 * 986 m ü. NN * flach geneigter Oberhang in unmittelbarer Nähe zum Albtrauf * 100° e-geneigt	**Bodennutzung**	Windwurffläche eines Tannen-Wald. in Sukzession begriffen



Horizont	Tiefe	Beschreibung
Ah	0-10 cm	[10YR2/2] * schluffiger Lehm * LD: gering * krü (sub) * karbonatfrei * sehr stark durchwurzelt *
IIBvAh	10-28 cm	[10YR3/4] * schluffiger Lehm * mäßig dicht * sub * karbonatarm * mittel steinig-grusig * stark durchwurzelt *
IIBvCv	28-45 cm	[10YR3/4] * schluffiger Lehm * sub * karbonathaltig * stark steinig-grusig * mittel durchwurzelt *
IIImCv	45-58 cm	[10YR5/4] * schluffiger Lehm * sehr karbonatreich * koh (Kalksplitter in Sandkorngröße sin) * sehr stark steinig-grusig * schwach durchwurzelt *

LEGENDE ZU DEN PROFILBESCHREIBUNGEN

► **Prozesse und Substrate**

- Humushorizont (Ah)
- Konkretionen
- Lessivierung (Al)
- Fe-, Mn-Flecken (beginnende Pseudovergleyung)
- Tonanreicherung (Bt)
- Holzkohlereste
- Verbraunung, Verlehmung (Bv)
- Pseudomycelien (sekundäre Kalkanreicherung)
- Schrumpfungsrisse
- Mergel
- Kalksteine

► **Horizontgrenzen**

scharf — deutlich — diffus

► **Abkürzungen**

Gefügeform

krü krümelig
sub subpolyedrisch
pol polyedrisch
pris prismatisch
koh kohärent
sin singulär

holozäne und pleistozäne Lagen (s. Übersicht)

OL Oberlage
HoL Holozäne Lage
HL Hauptlage
ML Mittellage
BL Basislage

Sonstiges

LD Lagerungsdichte
n.mb. LD des Feinbodens in sehr steinigem, grusigem Substrat mit Feldmethoden (Eindringwiderstand) nicht meßbar

Figure 2 *The documentation of a profile (GOMMEL, J. 1995, Anhang)*

	Ökotop A	Ökotop B	Ökotop C	Ökotop D
Vegetation	Blaugras-halde	Kalk-Magerrasen	Schwarzkie-fernforst	Schlehen-gebüsch
Hangneigung	39°	32°	33°	33°
C/N-Verhältnis	13	15	10	13
Nährstoffe: - Bedarf[1]	□	□	□	□
- Angebot	□	◩	■	■
- Korrelation	○	○	⚠	⚠
Kupfer-Verfügbarkeit	□	□	□	□
pH-Wert	▼	▽	▽	▽
Verbuschungs-Gefahr	□	□	■	■
Akt. Erosions-Gefährdung	◩	□/◩	□	□
Gründigkeit	□/◩	◩	◩	◩
Bodenfeuchte (mF; ÖF)	□	□	□	□

Erläuterung:

Nährstoffbedarf/Nährstoffangebot/Kupferverfügbarkeit/Verbuschungsgefahr/Aktuelle Erosionsgefährdung/Gründigkeit/Bodenfeuchte:

□ gering ◩ mittel ■ hoch

Nährstoff-Korrelation (= Verhältnis Bedarf - Angebot):

○ ausgeglichene Verhältnisse ⚠ Überangebot !

pH-Wert: ▽ sehr schwach alkalisch ▼ schwach alkalisch

1) = Bedarf von Kalk-Magerrasen (ELLENBERG 1986, S. 622f)

Figure 3 *The evaluation of different "Ökotops" (LEIENDECKER, T. 1991, Tab.7, p.59)*

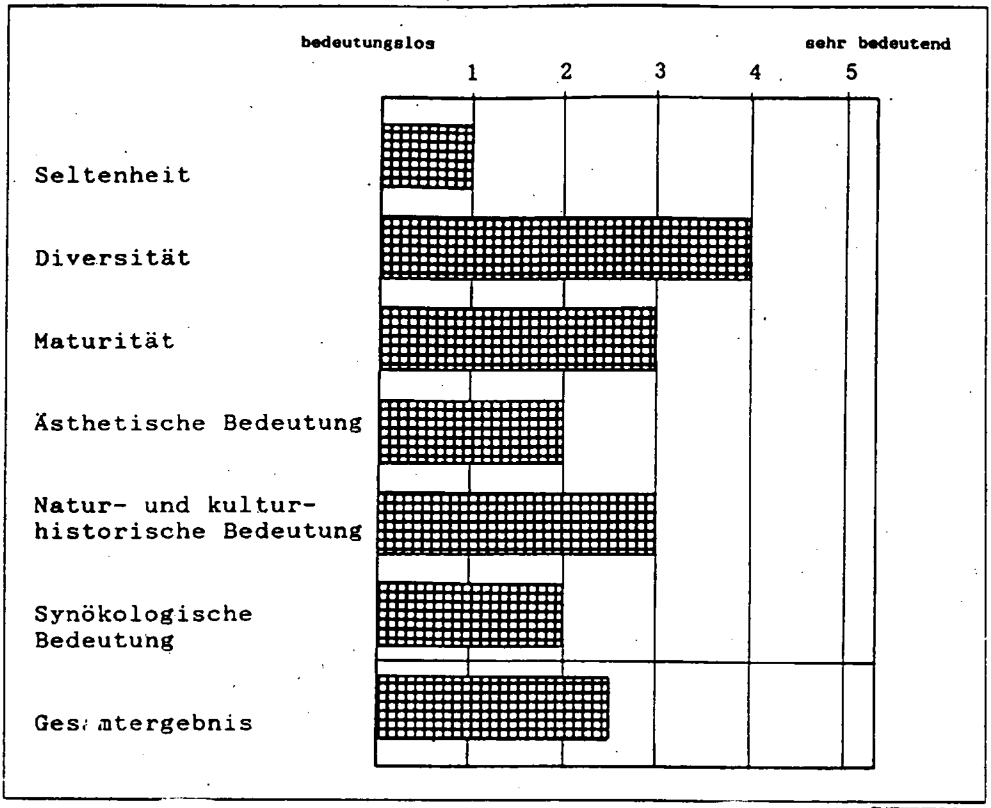


Figure 4 *The classification of a wet meadow under consideration of its protection value (ULLRICH, R. 1992, Fig.17, p.70)*

Furthermore, this submitted information can be processed into diagrams or graphs, like those being created by the author. These graphs which survey ecosystems were created for some parts of the karst regions located in the Mittelgebirges of southern Germany (Figure 5).

In addition, it is possible to create tabular summaries consisting of specific instructions that are only valid for certain regions. Table 2 shows an extract of the instructions for a planned nature reserve (HACK 1991). This table helps to estimate resulting costs and cultivation measures.

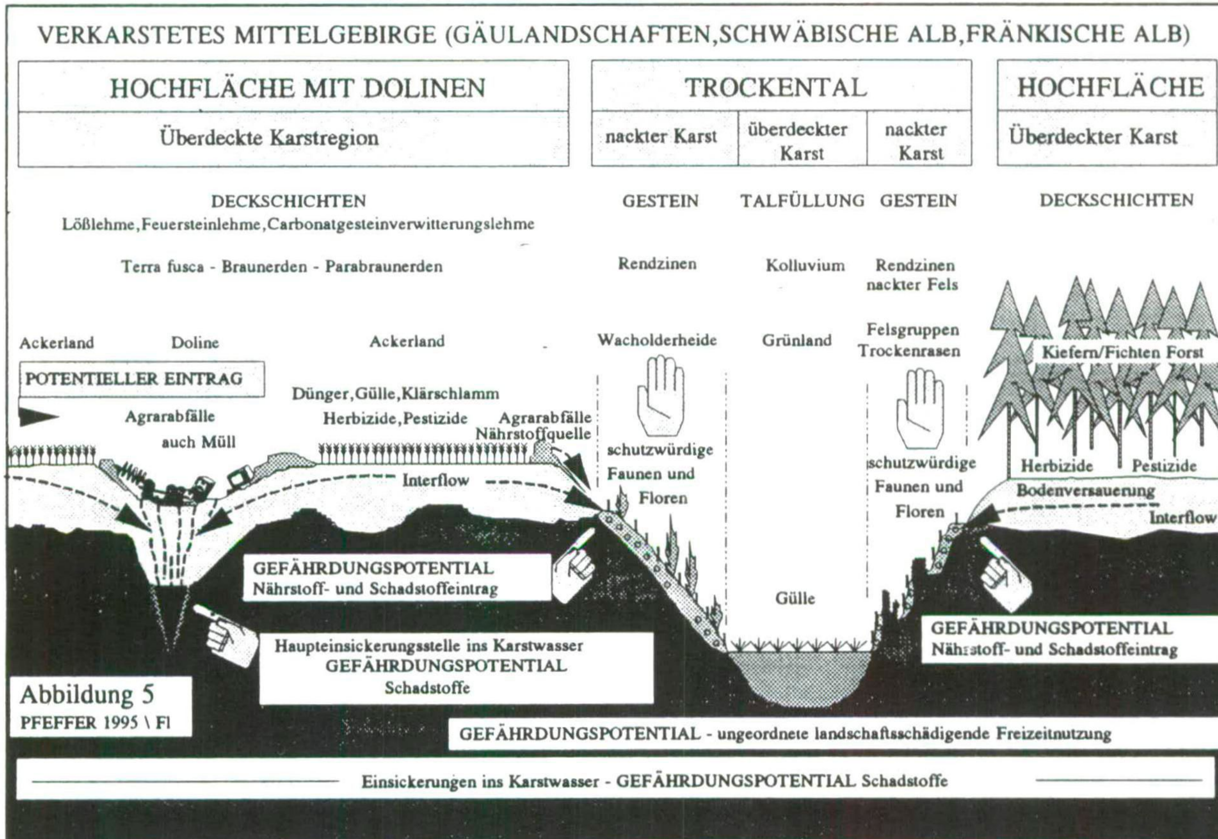


Figure 5 *The survey of an ecosystem showing ways of protection management*

Nr.	FLURSTÜCKNAME	BESCHREIBUNG / BEWERTUNG	PFLEGE / VORGESCHLAGENE MAßNAHMEN
1	Bauernofenbuckel 55 000 m^2	**Reine Wacholderheide, besonders hochwertige Flora** Wacholderheide von Gentiana verna-Brometum-Typ mit zahlreichen geschützten und seltenen Arten (u.a. Carlina acaulis, Daphne cneorum, Gentiana verna, Globularia punktata, Pulsatilla vulgaris). Wegen kleinsträumigen Wechsels von sehr flachgründigen, sandigen Rendzinen an vollsonnigen, trockenen Standorten und schattseitigen, frischeren Standorten, bzw. engen Dolomitsandgruben, bietet die Wacholderheide Bauenofen verschiedenste ökologische Nischen. Sie kann daher als ökologisches Kleinod bezeichnet werden.	Bewahrung des vielfältigen Charakters. Schaffung größerer schattenfreier Rasenflächen, bevorzugt im zentralen und südseitigen Teil. Stark verbuschte Bereiche auflichten, breitwüchsige Wacholder zurückstutzen, um wieder eine übersichtlichere Schafweide zu schaffen. <u>1. westlicher Teil</u> Erstpflege wurde durchgeführt. Dringend Nachpflege durchführen und die zahlreich aufkommenden Fichten- und Kiefernsämlinge "köpfen". <u>2. östlicher Teil</u> Wacholder vereinzeln; vor allem weitausladende Wacholder/-gruppen stark zurückstutzen. Fichten und Kiefern bis auf markante Einzelexemplare entfernen. Gebüsch in den Sandgruben schonen.
2	Spitzwald 35 000 m^2	**Wacholder-Buchenheide, hochwertige Flora** (u.a. Carlina acaulis, Daphne cneorum, Pulsatilla vulgaris). Kiefernsukzession auf sehr flachgründigen Rendzinen in Südexposition; wenig offene Rasenflächen bis hin zu lichtem Kiefernwald.	Schaffung eines baumfreien Halbtrockenrasen am Unterhang; hangaufwärts Übergang zu lichter "Wacholder-Kiefern-Heide"; NE-Ende: Freistellung der Weidbuchen mit Übergang zum Buchenmischwald. <u>1. Unterhang</u> Am NW-Ende wurden bereits Erstpflegemaßnahmen durchgeführt. Auf der gesamten Breite dringend Kiefernaufwuchs (1 bis 2m hoch) entfernen; zum NE-Ende hin Weidbuchen freistellen. <u>2. Mittelhang</u> Auf Gesamtfläche die schlechtwüchsigen Kiefern hangaufwärts zurückdrängen; als Übergang zum Buchenwald einen Saum aus lichtem Kiefernwald erhalten.
3	Alter Hau	**Stark mit Schlehen verbuschte Heide** Baumgruppe, Feldgehölz; Dolomitsandgruben.	Zwischen Weidebuche und Fichtengruppe Freiraum herstellen. Parkartiges Biotop anstreben. Verbund mit Spitzwald und Bauenofen. Im zentralen Teil das Schlehengebüsch entfernen, einzelne Fichten fällen.

Table 2 *The evaluation of several areas and suggestions for the protection management (extracted from table 7, HACK, T. 1991, p.76)*

7. Outlook

A new line of karst research in physical geography evolved by the application of these methodical techniques which were described by examples. In combination with the applied techniques of human geography, interest will be focused on this line. Due to the international cooperation with colleagues who are more interested in botanic and/or climatic ecology -like with the former department of Mr JAKUCS - new ways will be found to quantify the status quo of nature, as well as human impact in karst regions.

Furthermore, these new techniques also made a contribution to the successful international cooperation on a higher level due to the establishment of the "STUDY GROUP ON MAN'S IMPACT IN KARST" of the IGU and the emerged commission "ENVIRONMENTAL CHANGES AND CONSERVATION IN KARST AREAS" under the active chairman Ugo SAURO, Padova.

A new era of karst research in the context of research in karst ecosystems has begun throughout the world.

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9. References

ALTERMANN, N. 1993: Gliederung von pleistozänen Lagen. Mitt. Dtsch. Bodenkdl. Gesellsch. 72, S. 825-828.

ARBEITSGEMEINSCHAFT BODENKUNDE 1982: Bodenkundliche Kartieranleitung. 3. Aufl. Hannover.

BALÁZS, D. 1968: Karst-regions in Indonesia. Karszt- és barlang-kutatás, 5

BALLIF, Ph. 1896: Wasserbauten in Bosnien und der Herzogowina. Wien.

BAUER, F. 1962:Nacheiszeitliche Karstformen in den österreichischen Kalkhochalpen. Actes du Congres, 2.Intern. Speläol. Kongr. Bari 1958,Bd. 1., S.299-328.

BECK, R. et al. 1994: Laborskript - Ein Handbuch für die Benutzer der Laboratorien der Physischen Geographie der Universität Tübingen. Kleinere Arbeiten aus dem Geographischen Institut der Universität Tübingen, Heft 11.

BLUME, H.1968: Die Westindischen Inseln. Westermann, Braunschweig.

BÖGLI, A. 1961: Karrentische. Zeitschr.f.Geomorph. 5, S.185-193.

BÖGLI, A. 1978: Karsthydrogaphie und physische Speläologie. Springer, Berlin.

BOUZAT, D. 1969: Le Bassin de Cuges; Mediterranée 10.

BRAUN-BLANQUET, J. 1964: Pflanzensoziologie. 3. Auflage, Wien.

BUHMANN, D. & DREYBRODT, W. 1985: The kinetics of calcite dissolution and precipitation in geologically relevant situations of Karst. Chem. Geol. 48. S.189-211, 53, S.109-124.
CLAYTON, K. 1981: Explanatory Description of the landforms of the Malham area. Field studies 5, S.389-423.
CORBEL, J. 1954: Les phénomèneskarstiques en climat froid. Erdkunde 9, S.119-120.
CORBEL, J. 1959: Érosion en terrain calcaire. Anales de Géogr. 68. S.97-120.
CVIJIC, J. 1893: Das Karstphänomen. Pencks Geogr. Abh. 5,3. S.1-85
CVIJIC, J. 1918: Hydrogaphie soutteraine et évolution morphologique du Karst. Rec. Trans. Inst.Géogr. Alpine 6, S.375-426.
CVIJIC, J. 1924: The evolution of lapiés. Geogr. Rev. 14.
DANES, J.V. 1909: Geomorphologische Studien im Karstgebiete Jamaikas.Comte rendu des IX. Internationalen Geographenkongresses, Genf, 2, S.178-182.
DANES, J.V. 1910: Die Karstphänomene im Goenoeng Sewoe auf Java. Tijdschr. v.h. Kon. Nederl. AArdr. Genootsch. 2 Serie 27, S.247-260.
DAVIS, W.M. 1912: Die erklärende Beschreibung der Landformen, Leipzig u. Berlin.
DAY, M. 1979: Surface roughness as a discriminator of tropical karst styles. Z. Gemorph. Suppl.-Bd. 32, 1-8.
DENK, M. 1974: Meliorationen in Karstgebieten, aufgezeigt an nordmediterranen Poljen Staatsexamensarbeit Universität Frankfurt, unveröff.
DREYBRODT, W. 1988: Processes in karstsystems. Series in Physical Environment 4, Heidelberg.
EK, C. 1985: Comptes Rendus du Colloque International de Karstologie Applique, Liège.
ELLENBERG, H. et al. 1991: Zeigerwerte von Pflanzen in Mitteleuropa. Scripta Geobotanica, 18.
FUCHS, F., GERSTENHAUER A. & PFEFFER, K.-H. 1987: Herbert Lehmann, Beiträge zur Karstmorphologie. Erdkundliches Wissen, Heft 86.
FORD, D. & WILLIAMS, P. 1989: Karst Geomorphology and Hydrology, London.
GAMS, I. et al. 1987: Karst and Man. Ljubljana.
GAMS, I. & HABIC, P. 1987: Man's Impact in Dinaric Karst. Ljubljana.
GAMS, I. 1979: International comperative study of limestone solution by means of standard tablets. Actes du Sympos. Intern. sur l'érosion karstique. Aix-en-Provence, S.71-73.
GOMMEL, J. 1995: Bodenverteilungsmuster und Vegetation als Indikatoren der Landschafts- und Bodengeschichte im Bereich der Kuppenlandschaft der südwestlichen Schwäbischen Alb. Diplomarbeit Geogr. Inst. Tübingen, unveröffentl.
GERSTENHAUER, A. 1964: Blatt 3 (Nord-Puerto Rico) des Internationalen Karstatlas. Erdkunde 18, Beilage.
GRUND, A. 1914: Der geographische Zyklus im Karst. Zeitschr. Gesell. Erdkunde Berlin.52, 621-640.
HACK, T. 1991: Landschaftsökologische Bestandsaufnahme für das geplante Naturschutzgebiet "Bauenofen-Häuslesrain-Spitzwiesen", Mittlere Schwäbische Alb. Diplomarbeit Geogr. Inst. Tübingen, unveröffentl.
HASSERT, K. 1897: Der Fuciner See, einst und jetzt. Globus 72

JAKUCS, L. 1977: Morphogenetics of Karst Regions, Bristol.

JULIAN, M. 1992: Quelques réflexions théoriques sur le karst. in: Salomon & Maire 1992, S.17-30.

KATZER, F. 1909: Karst und Karsthydrographie. Zur Kunde der Balkanhalbinsel, Heft 8, Sarajewo.

KUNTZE, H., ROESCHMANN, G. & SCHWERDTFEGER, G. 1994: Bodenkunde. 5. Aufl.

KORNECK, D. & SUKOPP, H. 1988: Rote Liste der in der Bundesrepublik Deutschland ausgestorbenen, verschollenen und gefährdeten Farn- und Blütenpflanzen und ihre Auswertung für den Arten und Biotopschutz. Schriften für Vegetationskunde, Heft 19, Bad Godesberg.

LEHMANN, H. 1936: Morphologische Studien auf Java. Geogr. Abh. 3.Reihe, Heft 9, Stuttgart.

LEHMANN, H. 1954: Das Karstphänomen in den verschiedenen Klimazonen. Erdkunde 8, S.130-139.

LEHMANN, H. 1956: Report of the Commission on Karstphenomena. Intern. Geogr. Union IX General Assembly, Rio de Janeiro, 1956.

LEHMANN, H. 1964: State and Tasks of Research on Karst Phenomena. Erdkunde 18, S.81-83.

LEHMANN, H. 1970: Kegelkarst und Tropengrenze. Tüb. Geogr. Studien 34, S.107-112.

LEHMANN, H. & MORANDINI G. 1960: Vorschlag für einen vergleichenden Karstatlas auf der Basis freier internationaler Zusammenarbeit, vorgelegt von der Karstkommission der IGU. Zeitschrift für Geomorph. Suppl. Bd. 2 S.103-107.

LEHMANN, O. 1932: Die Hydrographie des Karstes. Leipzig und Wien.

LEIENDECKER, T. 1992: Der Haigergrund: Eine Naturschutzregion im Main-Tauber-Kreis - Landschaftsökologische Standortanalysen und Prognosen. Diplomarbeit Geogr. Inst. Tübingen, unveröffentl.

LESER, H. & KLINK, H.J. 1988: Handbuch und Kartieranleitung Geoökologische Karte 1:25 000. Forsch. Deutsch. Landeskunde, Bd. 228.

LOUIS H. & FISCHER, K. 1979: Allgemeine Geomorphologie, 4. Aufl., Berlin.

MARKS, R. et al. 1989: Anleitung zur Bewertung des Leistungsvermögens des Landschaftshaushaltes. Forschungen zur Deutschen Landeskunde, Bd. 229.

MAULL, O. 1938: Geomorphologie. Leipzig, Wien.

MIOTKE, F. 1974: Carbon Dioxide and the Soil Atmosphere. Abh. Karst- und Höhlenkunde, Reihe A, Heft 9, München.

MONROE, W. 1976: The Karst Landforms of Puerto Rico. Geol. Surv. Prof. Papers, 8

MUIR, D. & FORD, D. 1985: Castleguard. Ottawa.

NAUMANN, K.F. 1854: Lehrbuch der Geognosie. Leipzig.

NICOD, J. 1972: Pays et paysages du calcaire. Coll. le Géographe, SUP.

NICOD, J. 1982: Phénomènes Karstiques III. Mem. et Doc. CNRS.

PALMER, M.V. & PALMER, A.N. 1975: Landform development in the Mitchell Plain of southern Indiana: origin of a partially karsted plain. Zeitschr. f. Geomorph. 19, S.1-39.

PENCK, A. 1904: Das Karstphänomen. Schriften des Vereins zur Verbreitung naturwiss. Kenntnisse. Wien, 44.

PESCHL, O. 1869: Neue Probleme der vergleichenden Erdkunde als Versuch einer Morphologie der Erdoberfläche. Leipzig.

PFEFFER, K.-H. 1975: Zur Genese von Oberflächenformen in Gebieten mit flachlagernd Carbonatgesteinen. Wiesbaden.

PFEFFER, K.-H. 1976: Probleme der Genese von Oberflächenformen auf Kalkgesteinen. Zeitschr. f. Geomorph., Supplementband 26.

PFEFFER, K.-H. 1986: Zur Genese von Karstformen auf den Westindischen Inseln. Frankfurter Geogr. Hefte, 55.

PFEFFER, K.-H. 1986a: UIS International Atlas of Karst Phenomena. Zeitschr. f. Geomorph., Suppl. Bd. 59.

PFEFFER, K.-H. 1990: Süddeutsche Karstökosysteme. Beiträge zu Grundlagen und praxisorientierten Fragestellungen. Tübinger Geogr. Studien, 105.

PFEFFER, K.-H. 1990a: International Atlas of Karst Phenomena. Zeitschr. f. Geomorph., Suppl. Bd. 77.

PFEIFFER, D. 1963: Die geschichtliche Entwicklung der Anschauungen über das Karstgrundwasser. Beihefte z. Geol. Jahrbuch 57, Hannover.

PFEIFFER, P. 1991: Geoökologische Einheiten eines Limestone Pavement Gebietes, Hutton Roof Complex (SSSI), Cumbria, Nordwest England. Diplomarbeit Geogr. Inst. Tübingen, unveröffentl.

PHILIPSON, P. 1894: Der Kopais-See in Griechenland und seine Umgebung. Zeitschr. Gesellsch. f. Erdkunde, Berlin.

PRIESNITZ, K. 1974: Lösungsraten und ihre geomorphologische Relevanz. Abh. d. Akandemie d. Wissenschaften in Göttingen, Math.-Physik. Klasse, dritte Folge, Nr. 29, S.68-85.

REHFUESS, K.E. 1990: Waldböden - Entwicklung, Eigenschaften und Nutzung. 2. Auflage.

RICHTHOFEN, F. von 1886: Führer für Forschungsreisende. Hannover. Nachdruck Darmstadt 1973.

ROHDENBURG, H. 1971: Einführung in die klimagenetische Geomorphologie anhand eines Systems von Modellvorstellungen am Beispiel des fluvialen Abtragungsreliefs. 2.Aufl.

ROSSI, G. 1980: L'extreme nord de Madagascar. Aix-en-Provence.

SALOMON, J. N. 1987: Le Sud-Ouest de Madagascar. Etude de géographie physique. Bordeaux.

SALOMON J.N. & MAIRE, R. 1992: Karst et évolutiones climatiques. Bordeaux.

SANDERS, E.M. 1921: The Cycle of Erosion in a Larst Region (Cvijic). Geogr. Rev. 11, S.593-604.

SAWICKI, L.S. 1909: Ein Beitrag zum geographischen Zyklus im Karst. Geogr. Z. 15, S.185-204, S.259-281.

SCHEFFER, F. & SCHACHTSCHABEL, P. 1989: Lehrbuch der Bodenkunde. 12. Auflage.

SMALL, R.J. 1972: The study of landforms. Cambridge.

STRAHLER, A.N. 1969: Physical Geography.

SWEETING, M. 1964: Some Factors in the Absolute Denudation of Limestone Terrains. Erdkunde 18, S. 92-95.

SWEETING, M. 1972: Karst Landforms. Macmillan, London.

SWEETING, M. 1979: Problems in Karst Environments. Zeitschr. f. Geomorph., Suppl. Bd. 32.

TROLL, K. 1973: Beobachtungen von Tropenkarst in Thailand und Malaysia. Erdkundliches Wissen, Heft 32, S. 9-16.

ULLRICH, R. 1992: Das Upfinger Ried - eine landschaftsökologische Bestandsaufnahme eines Feuchtgebietes im Uracher Vulkangebiet auf der Schwäbischen Alb. Diplomarbeit, Geogr. Inst. Tübingen, unveröffentl.

VALETON, I. 1983: Klimaperioden lateritischer Verwitterung und ihr Abbild in synchronen Sedimentationsräumen. Z. Deutsch. Geol. Ges. 134, 1: 413-452.

WAGNER, G. 1960: Zur Flußgeschichte der Lone. Jahreshefte für Karst- und Höhlenkunde, Heft 1, S.193-210.

WHITE, W.B. 1988: Geomorphology and hydrology of karst terrains. Oxford.

WILLIAMS, P. 1993: Environmental changes and human impact. Catena Suppl. 25

ZÖTL, J. 1974: Karsthydrogeologie. Springer Verlag, Wien.

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DEFORESTATION AND KARREN DEVELOPMENT IN MAJORCA SPAIN

Angel GINES

ABSTRACT

The development of karren landforms begins, generally, beneath a soil cover. Once the soil has been removed by erosion, former subcutaneous karren features appear at the karst surface, being reshaped by the atmospheric agents. Just then, the overimposition of the most typical bare karren features, such as flutes (Rillenkarren), meandering runnels (Meanderkarren) and heelprints (Trittkarren), produces a characteristic sharpening of the rock. In Majorca, this kind of deforestation and soil loss processes can be efficiently studied within a geographical frame in which large karrenfields are present in different topoclimatic environments.

RESUMEN

El desarrollo del lapiaz comienza, por lo general, por debajo la cubierta de suelo. Después de que el suelo es retirado por erosión, aparecen morfologías de lapiaz subcutáneo que son remodeladas en contacto con los agentas atmosféricos. Sólo entonces se produce la sobreimposicion de las morfologías típicas de lapiaz subaéreo más características, como estrías, canales meandriformes y escalones. En Mallorca estos mecanismos de deforestación y pérdida de suelo pueden ser investigados eficazmente dentro de un marco geográfíco en el que los campos de lapiaz poseen una excepcinal diversidad topoclimática.

INTRODUCTION

Karren features are, probably more than dolines, the most widespread karstic landforms. If the term karren is generalized to any small-sized solutional sculpturing, as it is done in the more recent literature (SWEETING, 1972;BÖGLI, 1980; JENNINGS, 1985; WHITE, 1988; FORD & WILLIAMS 1989), every karstic terrain contains karren forms. Some of them are microscopic biokarstic features which share with the physico-chemical processes of limestone weathering a similar researching methodology. Others remain hidden under soil or buried by clastic sediments, as it happens with the typical subcutaneous karren features or cryptolapiaz (both terms can be considered synonymous). Finally, there are a great variety of karren forms, the better known, being exposed to open air so that their growth and development remain basically under the control of the atmospheric precipitations.

KARREN AND SOIL COVER IN THE EXOKARST

Most of the available literature on karren shaping processes is, nowadays, strongly biased towards those typical bare and soil-lacking karst features. These rocky environments are very characteristics of the deforested mediterranean area and also of the alpine regions, above the tree-line, where the research on karren was begun.

Obviously, the most conspicuous karren landforms are to be found on rocky outcrops on which the soil cover is less than 50 %. Even the etymology of the scientific terms lapiaz and karren reflects presumably a certain relation to the latin word lapis and the pre-indoeuropean term (stem) karra, both meaning rock. Furthermore, the sharp crests, the meandering runnels, the heelprints and flutes, that constitute the most striking karren features, are only formed when the limestone remains directly exposed to the karstic erosion of rainfall. On a larger scale, the term Karrenfeld or Karrenfield that stands for assemblages of karren landforms wider than several square kilometres wouldn,t make any sense in karstic terrains entirely covered by soil and vegetation.

Only once the pedological cover has been removed, either by natural or artificial processes,it is possible to observe the subcutaneous karren features developed on the bedrock surface beneath the soil. Artificial cuts in quarries and roads allow verification of the efficient growth of the subsoil karren (cryptolapiaz) in such an environment, characterized by the presence of high carbon dioxide concentrations as well as by a slow infiltration of water. Also, below detritic cover of glacial or periglacial origin quite similar solutional features can be formed.

The existence of subcutaneous karren features, or cryptolapiaz, was implicity assumed in several classifications of karren landforms developed on the basis of the works published by BÖGLI (1960, 1980). So three main genetic categories are distinguished: bare or free karren, half-free karren and covered karren. Later studies emphasized the role played by the subsoil corrosion in the evolution of karren morphologies in particular (GAMS, 1973) and exokarst in general (JAKUCS, 1977). Due to this, in a more explicit way, a recent publication affirmed that great areas of karren topography develop under a continuous soil and plant cover (FORD & WILLIAMS 1989); at the same time it is mentioned that many regional geomorphologic studies ignore such fact.

Among other original contributions to the knowledge about soil-bedrock interactions on karstic terrains, the subchapter titled Modifications in erosion due to the changes in the natural plant cover of a karst region (JAKUCS, 1977) introduces a new evolutionary explanation when referring to the Aggteleki-Karszt. According to JAKUCS (1977) not only the Aggtelek karren landforms, but also the karrenfiels of the Dalmatian Karst, indicate a gradual transformation of formerly rounded and smooth shapes, produced by subsoil corrosion, towards characteristic features of sharp grooves and furrows formed in subaerial conditions. This transformation results from rock denudation, after the plant cover decay and the soil dissection advances.

A TWO-STAGES-MODEL OF KARREN DEVELOPMENT

As the available knowledge on karren development under soil has increased, the covered karren (subcutaneous karren) has ceased to be a set of solutional landforms of more or less anecdotic interest. In fact, almost every karst is or has been a covered karst. Just exceptionally, under extreme bioclimatic conditions, the exokarst evolves without any soil cover on it.

As indicated above, karstic corrosion on limestone outcrops is much more intense beneath the soil, due to the high carbon dioxide concentration registered there, and also due to the long time periods in which water remains in contact with the bedrock. It is not going too far to state the greatest amount of limestone that has been dissolved in the karrenfield over some time would have been exported when the current karrenfields were still covered beneath a layer of soil and vegetation. It is an extraordinary paradox that the most spectacular and striking landforms constituting the bare karren show potential denudation rates much lower than those corresponding to hidden subcutaneous karren. The two-stages-model for karren development assumes that the bulk of the forms observed in a karren outcrop are shapes generated when the bedrock was still buried below the soil covering. It should be remembered that, as karren sculpturing is mainly subtractive, the greater the limestone volume removed by dissolution, the greater the morphological effect will be.

When analysing thoroughly some of the main Majorcan karrenfields it is easy to find numerous hollows, pits, tubes and small cavities generated by subsoil corrosion on the sides of karren pinnacles as well as on many barren ground surfaces of karstified limestone. Such relict features of subcutaneous karren appear to be reshaped by the growth of bare karren features which modifies them substantially. Recent studies suggest that, even the bigger karren landforms, as those several-meters-high karren pinnacles of the stone forest, could have been formerly generated as covered karren (CHEN et al. 1986).

The two-stages-model for karren development assumes that under relatively steady geoecological conditions, beneath a natural plant cover and a mature soil developed in equilibrium with the climate, an intense growth of subcutaneous karren is produced. This model attributes great importance to the soil loss mechanisms because possibly these are able to override the rate of soil formation. Then, the karren morphologies generated under the soil will rise to the ground surface. Usually, the drastic increase in the rate of soil stripping corresponds to ecological crisis, as those produced by climatic changes. The deforestation provoked by man also accelerates the soil washing, as the erosion is enhanced. After soil dissection, the tops of some subcutaneous karren-pinnacles gradually emerge, being transformed by subaerial karren features. The overimposition of new solutional features generated by rainfall and runoff waters, in contact with the atmosphere, would complete this two-stages-model which can be applied in the most significant karren landscapes in warm and temperate climates.

SOME EVIDENCES FROM MAJORCAN KARST IN FAVOUR OF THE MODEL

The Serra de Tramuntana (main mountain-range of the island of Majorca) shows many evidences of the two-stages-model being valid in those karren areas located on the summits as well as in those karrenfields set on the sides and the surroundings of the mountains. All along the altitude range of the Serra, from 0 to 1400 meter a.s.l., relict features of rounded subcutaneous karren are common. At the same time, progressive transformation of subsoil-generated tubes and hollows through reshaping by typical bare karren features is observed.

In Majorca the geographical conditions are very suitable to study the relations between karren evolution and soil removal caused by deforestation processes (GINES, 1990). Due to its altitude, the Quaternary glaciations just reached to produce cold climates and small periglacial environments in the Serra de Tramuntana heights, where they could have caused recurrent bioclimatic crisis of moderate strength. Also human activity could have been an important cause of deforestation, since man settled the island for approximately 8000 years ago. Finally, the exceptional degree of karstification observed in some sectors of the Serra de Tramuntana permits to envisage a possible autodeforestation mechanism yet not stated in the bibliography: some kind of wood-subsidence promoted by vertical soil loss through large cracks widened by karstic solution.

In the Majorcan karrenfields limestones are very pure. So, a scanty amount of insoluble-minerals residuum produced during karstification generates a slow pedogenesis. If the soil formation rate is very low, any disturbance which facilitates an increase of the soil removal rate might provoke an irreversible unbalance. Climatic changes, forest destruction and easy washing of small soil particles, all along the hillslides and also through karstified fissures, are the main mechanisms which can initiate the emergence upon the ground surface of subcutaneous karren forms that appear as the soil stripping advances (Fig. 1).

BIOCLIMATIC CRISIS RELATED TO GLACIATIONS

The recurrence of permafrost and cold climate phases in the summits of the main Majorcan mountains during the Quaternary might have implied the recession of the forests towards lower elevations as well as severe damages to the soil mantle. Probably, each phase of cold climate caused a real ecological crisis at altitudes over 800 metres a.s.l. in the Serra de Tramuntana mountain-range. The substitution of forests with scrubs and grass formations, more resistant to biological stress but less protective against soil erosion, produced a progressive natural soil profile degradation in the highest areas.

When the periods of cold climate came to an end the plant communities recovery was seriously hindered by the slow rate of soil formation, as the greatest part of the Majorcan highest areas is constituted by very pure carbonated rocks in which the amount of clay and clastic debris is negligible. Moreover, the soil mantle impoverishment was accompanied by the denudation of ancient covered karren. So that the resettlement of the

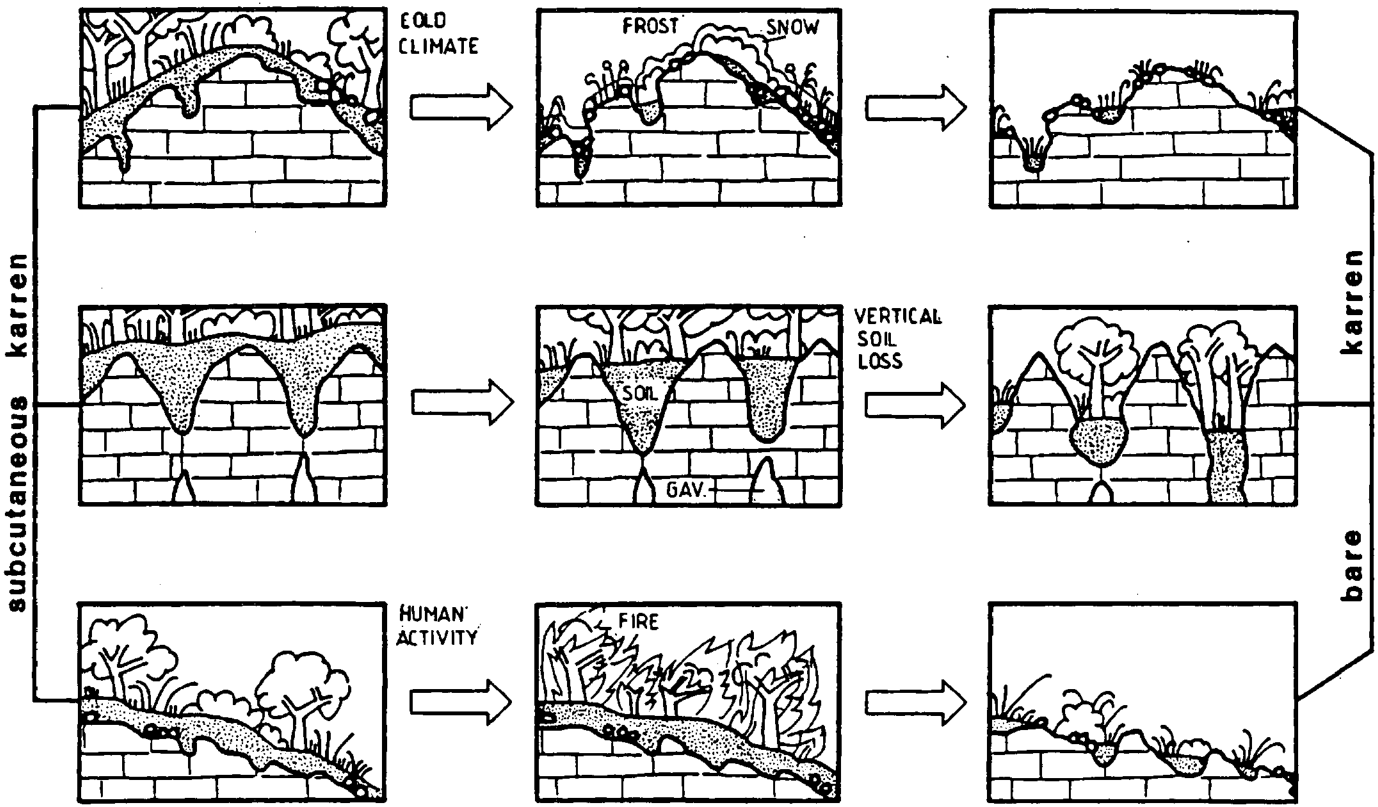

Figure 1 *Development of subcutaneous karren*

forest species resulted each time less efficient. The stony nature and sharpness of these landscapes was enhanced, specially in the areas characterized by steep slopes. Nowadays, the karren landforms located at the summits of the Serra de Tramuntana mountains (over 800 metres a.s.l.) show abundant bare karren features, with some periglacial inherited influences and with some locally dispersed remains of relict subcutaneous karren features.

DEFORESTATION AND SOIL REMOVAL CAUSED BY MAN

As a general rule human activity tends to simplify the initial complexity of the ecosystems and also tends to upset the bioclimàtic equilibrium conditions that control the action of the main agents and geomorphological factors. Human settlement in Majorca, a little more than 8000 years ago, necessarily brought about changes both in the plant cover and in the predominant erosion mechanisms. It is possible that during the first four millenniums human activity had little ecological consequences. But the men of different cultures who subsequently inhabited the island produced important cattle-raising and farming changes, so causing the regression of the steady-state forests of Quercus ilex and also of the more thermophile ones of Pinus halepensis. The Roman colonization happened in 123 B.C., but the greatest agricultural changes in Majorca took place during the Muslim epoch, between the IX and the XIII centuries.
Woodfires have historically been the main cause of the plant cover decay in the Majorcan karst. To the former deforestation, due to the seeking of larger agricultural areas, it must be added the deeply rooted habit of periodically burning the brushwood in order to renew the grazing-lands. The traditional activity based on the repetitive burning of herbaceous brushwoods of Ampelodesmos mauritanica, for cattle pasturing, has become the more strong human activity in the representative karrenfields of the Serra de Tramuntana. The active soil removal produced after the deforestation and the progressive degradation of scrub formations, leads to a gradual increase of the bedrock surfaces exposed to open air. n these cases, the growth of subaerial karren morphologies is limited by the time elapsed since the dissection of the subcutaneous karren took place.

WOOD SUBSIDENCE PROMOTED BY KARSTIFICATION

In some strongly karstified limestone plateaux from the Serra de Tramuntana mountain-range, such as the one surrounding Lluc, tall karren pinnacles outstand over the Quercus ilex forest. It seems as if the forest would have sunk down among the deep spaces which exist between the karren pinnacles, accompanying the gradual soil, lowering. It would be more appropriate to talk about a "subsidence" or à settling of the natural soil-forest mantle as a whole, rather than to refer to an authentic deforestation.

The bizarre landscape resulting from this karstic process of "wood subsidence" is enough to produce intransitable groups of rocky edges and almost vertical pinnacles which rise above woodlands confined among them. On top of these limestone-pinnacles the bare karren features are remarkably developed, while 10 or 20 metres below them, at the foot of the pinnacles, the subcutaneous karren features are predominant.

The several limestone plateaux, where such a noteworthy karrenfields present moderate slopes, show well developed joint systems and furthermore they seem to have undergone a very long karstic evolution (that perhaps comes from the end of the Tertiary, according to BÖGLI, 1976). Probably a long time ago, when the limestone platform was being karstified, the surface was buried by ancient soils coming from the decay of clays, marls and volcanic rocks of the Upper Triassic (Keuper). It seems as if the intense karstification was enough to produce a substantial solutional enlargement of the main cracks until the rate of vertical soil loss through major fissures exceeded the slow current rate of soil formation on the almost pure karren-bearing limestones. From that moment on, the deepening of both the soil and its natural plant cover provoked a progressive rise of karren pinnacles above the level of the forest.

CONCLUSIONS

It is necessary to extend the karstic research on the physico-chemical and pedological processes that are involved in the development of the karren morphologies which are formed under a soil cover. Further studies should be performed in order to know the morphometry, the most significant characteristics and the distinctive diagnostic features related to the subcutaneous morphogenetic environment. It is also interesting to make carefully observations on the several phases of the sequence: deforestation - soil removal by erosion - and overimposition of bare karren features. Detailed studies of the different deforestation mechanisms, as well as of the time-span during which each one of them has been active on the Majorcan karrenfields, could allow the acquisition of approximate estimations of the rates of soil loss and karstic denudation.

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REFERENCES

BÖGLI, A. (1960): "Kalklösung und Karrenbildung". Zeitschrift für geomorphologie, N.F. suppl. 2:4-21. Berlin

BÖGLI, A. (1976): "Die wichtigsten Karrenformen der Kalkalpen". in Gams, I. Ed. "Karst processes and relevant landforms", International Speleological Union, Symposium on karst denudation: 141-149. Ljubljana.

BÖGLI, A. (1980): "Karst Hydrology and Physical Speleology". Springer-Verlag, p.284 Berlin.

CHEN ZHIPING;SONG LINHUA & SWEETING, M.M. (1983): "The pinnacle karst of the Stone Forest, Lunan, Yunnan, China: an example of a sub-jacent karst". in Paterson, K. & Sweeting, M.M. Eds. "New directions in Karst", Geobooks, Regency house, 33:597-607.

FORD, D.C. & WILLIAMS, P.W. (1989): "Karst Geomorphology and Hydrology". Unwin Hyman Ltd., p. 601.

GAMS, I. (1973): "Forms of subsoil karst". Proceedings of the 6th International Congress of Speleology. Vol. II. p. 169-179. Olomouc.

GINÉS, A. 11990): "Utilizacion de las morfologías de lapiaz como geoindicadores ecológicos en la Serra de Tramuntana (Mallorca)" Endins, 16:27-39. Palma de Mallorca.

JAKUCS, L. (1977): "Morphogenetics of karst regions. Variants of karst evolution". Akadémiai Kiadó, p. 284. Budapest.

JENNINGS, J.N. (1985): "Karst Geomorphology". Basil Blackwell Ltd., p. 293. Oxford.

SWEETING, M.M. (1972): "Karst Landforms". The Macmillan Press, p. 362. London.

WHITE, W.B. (1988): "Geomorphology and Hydrology of Karst Terrains" Oxford University Press p. 464, New York

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THE ROLE OF STRONG ACID IN SPELEO-INCEPTION AND SUBSEQUENT CAVERN DEVELOPMENT

D.J. LOWE - J. GUNN

ABSTRACT

In this paper we examine alternatives to conventional views which suggest that carbonate speleogenesis is achieved by the single process of carbonic acid dissolution. Various dissolutional mechanisms, including those involving sulphuric acid, are discussed with particular emphasis upon their potential role during the earliest, inception, phase of speleogenesis. Minerals that can break down to produce sulphuric acid, with or without microbial mediation, occur as trace components in most carbonate sequences, but they are more concentrated at specific levels. These levels comprise beds of atypical lithology, together termed inception horizons, and are commonly associated with breaks between major depositional cycles. Examination of earlier results that have referred to 'special' cases of carbonate dissolution leads to the suggestion that these are better described as 'extreme' cases, and that the processes described are dominant during inception and ubiquitous during later speleogenesis. Selected studies outside mainstream cave research are re-examined and it is noted that processes and mechanisms active in non-carbonate rocks are equally likely to affect carbonate sequences.

INTRODUCTION

The chemical processes by which limestone is dissolved in water containing dissolved carbon dioxide are well understood and discussed in detail in many texts (eg Ford & Williams, 1989). These processes are of undoubted importance in the subaerial dissolution of limestone, in dissolution at the soil-limestone interface and in the development of surface and underground landforms. However, as Howard (1964) pointed out, caves ought not to form if carbonic acid dissolution alone drives speleogenesis, since infiltrating solutions will become saturated before they can penetrate sufficiently into the limestone. Later kinetic modelling by Dreybrodt (1990) and Groves & Howard (1994a, 1994b,1995) suggests that at least in theory the effects of carbonic acid dissolution may penetrate further and persist longer than originally thought. However, the models still require the presence of primary voids through which initial water movement takes place and they do not explain the common phenomena whereby cave passages are concentrated at specific levels within most carbonate sequences.

In his earlier paper, Howard (1964) deduced that for speleogenesis to begin, acid must be generated in the rock mass and theorised that acid could be generated by inorganic or bacterial oxidation of rock sulphides or organic matter in groundwater, as suggested by Kaye (1957). Similar conclusions were drawn by Durov (1956; English translation 1979, p.186) who stated: *"During the evolution of karst features ... in carbonaceous* [sic] *rock (limestone and dolomite), the solvent is water containing carbonic acid. Generally no mention is made of any other agents promoting rapid solution of bedrock. However, A Saukov points to the particular significance of the products of oxidation of sulfinds* [sic; ?sulphides] *and above all sulfuric acid in those regions where carbonaceous rocks (limestone) prevail. As Saukov has said, the resulting solutions 'pave themselves a way' in the calciferous rocks; during that time the karst process is abruptly reinforced, which promotes the rapid advance of the lower boundary of the zone of oxidation attaining in such cases a depth of 100 meters from the surface".* Although later work, notably by Jakucs (1977), showed that carbonate dissolution by strong acids, especially sulphuric acid, is a sound theoretical possibility, those case studies that have provided evidence for alternatives to carbonic acid dissolution (eg Morehouse, 1968; Egemeier, 1981; Van Everingden and others, 1985; Hill, 1987) have been labelled as *'special'* or *'aberrant'* situations.

It is widely assumed that dissolution due to sulphuric acid is unimportant, because analyses of water from active underground drains rarely include significant amounts of anions such as 'sulphate'. An alternative explanation of the available evidence is that most anions in limited inception flows comprise sulphate, but this dominance decreases as conduits enlarge. Carbonic acid by-product levels increase significantly relative to those of sulphate after turbulent breakthrough. A still more significant jump occurs on transition from phreatic to vadose conditions. Sulphate (or other strong acid related anion) values in water from vadose and shallow phreatic systems are swamped by the bicarbonate ions. Flows from artesian or deep phreatic elements in multi-level systems contain significantly higher sulphate concentrations and relatively less bicarbonate (Worthington, 1991; Worthington & Ford, 1995).

More contentious than potential sulphuric acid involvement in speleogenesis, are questions of its scale and importance. These questions have rarely been viewed objectively though the concept has been applied to *'special'* cases. We prefer to view the *'special'* cases of earlier workers as **'extreme'** examples of a widespread, possibly ubiquitous, aspect of speleogenesis and believe that the scale of strong acid effects has been misunderstood and their importance relegated to obscurity. We argue that in many carbonate sequences the earliest stage of conduit development, which we refer to as inception (Lowe, 1992), is likely to be dominated by sulphuric acid dissolution and related processes and that, as the conduits enlarge, this dominance decreases. Regrettably there have been relatively few analyses of sulphate ions in karst groundwaters, especially from inception situations, and hence, in this paper, we draw on published case studies and indirect evidence to support our arguments.

THE CHEMISTRY OF THE SULPHURIC ACID REACTION

At the centre of many reactions suggested as contributory to the ultimate dissolutional mechanism is the interaction of sulphuric acid and calcium carbonate to produce calcium sulphate, water and carbon dioxide:

$$H_2SO_4 + CaCO_3 \leftrightharpoons CaSO_4 + H_2O + CO_2$$ (eg Jakucs, 1977, p.48)

This may be written in other ways, such as:

$$H_2SO_4 + H_2O + CaCO_3 \leftrightharpoons CaSO_4 \cdot 2H_2O + CO_2$$ (eg Helz and others, 1987, p.431)

or:

$$H_2SO_4 + CaCO_3 + 2H_2O \leftrightharpoons CaSO_4 \cdot 2H_2O + H^+ + HCO3^-$$ (Ford and Williams, 1989)

It might appear that the reaction is irreversible under temperature and pressure conditions in the cave environment, yet it can proceed from right to left. For example, Klimchouk (1986) found that in some Ukrainian gypsum caves, condensation water containing dissolved carbon dioxide dissolves gypsum roof or wall rock and precipitates calcium carbonate. In the context of normal carbonate speleogenesis, the left to right reaction is essentially irreversible, but in the reduction zone the reaction may be reversed, depending upon the prevailing Eh (Oral communication, Dr T K Ball, British Geological Survey, 1991). Carbon dioxide produced by the sulphuric acid reaction can react to dissolve more calcium carbonate, a potential for enhanced dissolution termed the *'doubled solvency effect'* by Ford and Williams (1989, p.75). Ball and Jones (1990, p.5) reported: *"When consideration is taken of the mass balances and of the different densities of the minerals, one volume of totally oxidised pyrite can result in the dissolution of a further six volumes of calcite."*.

CASE STUDIES OF SPELEOGENESIS BY STRONG ACIDS

Level Crevice cave, Iowa, United States

Level Crevice Cave, Iowa, was opened to the surface by mining activity (Morehouse, 1968). It is unclear whether the absence of a surface connection was due to an impermeable cover or whether connections smaller than the anthropocentric limit (the limit of human accessibility) pre-existed. If the former, the point is significant as few earlier authors acknowledged that caves (other than isolated dissolutional chambers) could form without surface input and output points. The cave is formed in the Middle Ordovician Galena Formation and has three bedding-parallel levels or tiers. The bedrock is dolomite, and calcite, pyrite, marcasite, galena and limonite occur in the cave. Morehouse described the cave as *"joint controlled"*, but stated: *"The cave passages also appear to have been controlled by development at favourable stratigraphic levels...."* (1968, p.2). This stratigraphic control, previously noted by Howard (1960), was linked to differential bedrock fracturing or brecciation, and uneven solubility due to varied porosity and chemical composition. Water analyses showed that: *"...sulfate ion is present in the cave waters in fairly large concentrations."* (1968, p.7), and Morehouse concluded that sulphuric acid dissolution was dominant in the cave. The reaction chain deduced by Morehouse is:

Step A $4FeS_2 + 15O_2 + 2H_2O \Rightarrow 2Fe_2(SO_4)_3 + 2H_2SO_4$
Step B $2Fe_2(SO_4)_3 + 12H_2O \Rightarrow 4Fe(OH)_3 + 6H_2SO_4$
Step C $4Fe(OH)_3 \Rightarrow 2Fe_2O_3.nH_2O$
Step D $8H_2SO_4 + 8Ca{\cdot}Mg(CO_3)_2 \Rightarrow 8Ca^{2+} + 8Mg^{2+} + 8SO_4^{2-} + 16HCO_3^-$
Step A + *Step B* + *Step C* + *Step D*:
$4FeS_2 + 15O_2 + 14H_2O + 8Ca.Mg(CO_3)_2 \Rightarrow 2O_3{\cdot}nH_2O + 8Ca^{2+} + 8Mg^{2+} + 8SO_4^{2-} + 16HCO_3^-$

Morehouse pointed out that the stoichiometry of the sulphuric acid reaction should produce a sulphate ion concentration half that of the bicarbonate ion and his analytical results agreed with this ideal ratio within 4%. Other observations supported the view that sulphuric acid dissolution dominates in the cave. Massive and disseminated pyrite and marcasite occur in the wall rocks and Morehouse (1968, p.10) stated: "*...it does not take much sulfuric acid (or, therefore, much pyrite or much marcasite) to significantly affect cave development.*". The cave waters were saturated in dissolved oxygen at all times. Limonite ($Fe_2O_3.nH_2O$) was present within the dolomite wall rocks in amounts between 0.9 and 2.3%. No sulphate concentrations exist near the cave to account for high sulphate values in the analyses. Lack of seasonal fluctuation in analytical data suggests that dissolution is independent of carbon dioxide levels in overlying soils. Finally, *'valley bars'*, where passages narrow beneath surface valleys, are reciprocal to expectation if carbonic acid dissolution were dominant. In the latter case dissolution should be greater where percolation passes through less bedrock and has less opportunity to achieve saturation. Larger passages would be expected at these points. In the case of the sulphuric acid reaction, downward percolating water is acidified in passing through the overlying rock, being theoretically less acidic where the rock is thinnest, beneath valley floors. The validity of this argument is uncertain, as laterally moving water must contribute to development, and vertically descending water must constantly be reacting with carbonate in penetrating the bedrock.

As an alternative to Step A, Morehouse suggested that iron bacteria *(Crenothrix* and *Gallionella)*, common in the cave, gain energy by oxidising ferrous to ferric iron:

Alternative Step A: $4FeS_2 + 15O_2 + 14H_2O \Rightarrow 4Fe(OH)_3 + 8H_2SO_4$

Ferric hydroxide excreted by the bacteria rearranges as in Step C of the inorganic mechanism. Morehouse noted that equal numbers of moles of pyrite/marcasite, oxygen and water are used in the inorganic and bacterial reactions and that the same number of moles of sulphuric acid are produced. Whichever mechanism operates, the result is the same. Morehouse concluded that the primary development [inception] of the cave was achieved by the sulphuric acid reaction under artesian conditions, as outlined by Howard (1964). He reasoned that artesian conditions developed because the Galena Formation was sealed beneath the Maquoketa Shale, except where relatively few, steep valleys, such as those cut by glacial meltwater, had incised the carbonate sequence. This supports the proposed chemistry, as percolation reaching the cave level would have reached equilibrium with respect to the carbonic acid reaction, but still be saturated with oxygen. The general reasoning and proposed reactions remain basically sound, but it is no longer certain that the inferred linking of inception to Quaternary time (by reference to downcutting by glacial streams) is realistic (Lowe, 1992). The cave was drained by mining, so at least part of the system had not reacted to surface downcutting by that time. Inception by the Howard (1964) mechanism could long have been active before breakthrough to turbulent flow conditions and before the cave acquired its present dimensions.

Cave development by thermal waters

(Egemeier, 1973, 1981), studied cave development by thermal waters and *'replacement solution'*, in the Big Horn Basin of Wyoming, where much underground drainage penetrates a confined carbonate aquifer, the Madison Limestone. The broadly synclinal basin includes local anticlines, some cut by surface river canyons. Water from recharge areas (Absaroka and Big Horn mountains) around the basin, traverses the confined aquifer under artesian conditions, discharging from non-thermal springs near the mountains, or warm springs where canyons cut anticlines within the basin. Deep flow, up to 2000 m beneath the surface in the main axial area, and commonly 1000 m down across much of the basin, is responsible for the temperatures of the thermal springs. Artesian springs discharge thermal water containing dissolved hydrogen sulphide into open caves. Though not specified by Egemeier, presumably the water issues from conduits extending to great depth within adjacent synclines. The artesian head is provided by the greater elevation of remote, synclinal limbs in the mountainous recharge areas. Egemeier did not identify the origin of the hydrogen sulphide but, by implication, it derives from gypsum in the Madison Limestone. Elevated temperature and pressure enable supersaturation, and degassing is inevitable as spring water encounters cave air. Some hydrogen sulphide reacts with oxygen as the spring water dissolves cave air, generating sulphuric acid. This attacks calcium carbonate in the stream bed. Hydrogen sulphide escaping into the cave air redissolves in oxygen-rich water on cave walls and ceiling, forming sulphur and sulphuric acid. Airborne fallout of sulphuric acid is probably formed, as described by Van Everingden and others (1985), but this was not noted by Egemeier.

$$H_2S + 2O_2 \leftrightarrows H_2O + SO_3$$
$$2H_2S_{(aq)} + O_{2(aq)} \leftrightarrows 2S_{(s)} + 2H_2O_{(l)}$$

Elemental sulphur is oxidised further, with or without mediation by bacteria such as *Thiobacillus* spp and *Sulphobus* spp (Ehrlich, 1981), generating additional sulphuric acid:

$$2H_2O_{(l)} + 2S_{(s)} + 3O_{2(aq)} \leftrightarrows 2HSO_4^-{}_{(aq)} + 2H^+{}_{(aq)}$$

Limestone (or dolomite) is then attacked to produce gypsum (or gypsum and epsomite):

$$H^+{}_{(aq)} + HSO_4^-{}_{(aq)} + CaCO_{3(s)} + H_2O_{(l)} \leftrightarrows CaSO_4.2H_2O_{(s)} + CO_{2(g)}$$

Solid gypsum (or gypsum and epsomite) begins to redissolve in cave water immediately, if the two are in contact. Crystal crusts formed above water level on passage walls and ceilings eventually fall, due to increasing weight, and cave streams dissolve them or carry them away. This basic chemistry agrees well with processes described by other workers, and with more general reactions described by Ehrlich (1981).

Egemeier (1981, p.39) noted that: *"The Madison contains breccias that may represent a previous karst cycle of erosion. They are, however, cemented into solid rock today. Where they are cut by the caves there is no evidence of influence on the cavern passage."*. As there are no known abandoned passages associated with the spring, Egemeier described the Big Horn caves as *'one cycle'*, referring back to the theories of W M Davis (1930). Egermeier studied accessible caves carrying water to springs, or *'dead'* caves, assumed to be of similar origin but there was no consideration of the guidance of, or processes involved in, cave inception. Describing a second aquifer, the Tensleep Sandstone, Egemeier concluded that the Madison Limestone is the better aquifer because its hydraulic gradient is more favourable than that in the sandstone. However, he did not question whether this was always so, or if it reflects cavernization in the limestone.

We argue that it is invalid to assume that the Madison Limestone always provided a ready pathway for underground drainage. If speleogenesis depended solely upon input to and output from an artesian system imposed after formation of the Big Horn Basin, how did water initially enter the aquifer in the recharge areas? Was the Madison Limestone permeable or impermeable when the aquifer was exhumed from beneath shale caprock in the recharge areas? Was there already a secondary, joint or fault linked, permeability? It is unrealistic to assume tacitly that, after caprock erosion in the recharge areas, water simply entered the Madison Limestone, worked its way down-dip to great depth in the synclinal core and then rose again towards the crests of unroofed anticlines, **at which time and at which locations** speleogenesis due to strong acid dissolution began. Egemeier may have been misled in asserting that relict karst features are not implicated in current cavern development, as Sando (1988) subsequently described an extensive palaeokarst suite within the Madison Limestone. Sando (1988, p.264) considered that: *"The geometry of later caves was undoubtedly overprinted on these ancient features."* He also refers to *"a significant paleohydrological conduit"* in an evaporite [gypsum] zone at the base of a component member of the Madison Limestone, and to a zone of evaporite leaching at the base of a higher member. Though not stated explicitly, potential links can be deduced between palaeokarst features in the Madison Limestone, palaeo-conduits and, in view of the crucial involvement of evaporite minerals in Egemeier's dissolution mechanism, current speleogenetic activity.

Concatenation of Egemeier's dissolution mechanism and Sando's observations of Madison Limestone palaeokarsts suggests that the speleogenetic history is longer and more complex than Egemeier supposed. Speleogenesis affected parts of the Madison Limestone during its deposition, and caves existed before folding produced the basin. Whether open voids remained when deformation began, or whether all were filled by younger deposits is unknown; leaning to Egemeier's viewpoint the latter must be assumed. Nevertheless, infill would offer potential drainage routes if possessing less hydraulic resistance than the primary rock. Sando's comment that cave geometry is superimposed upon ancient features, suggests regeneration of earlier routes. Supposed links between palaeo-hydraulic routes and evaporitic horizons (Sando, 1988) suggest other theoretical connections. The possibility that hydrogen sulphide required by Egemeier's (1981) reaction is formed by reduction of evaporites cannot be ignored. Sulphate reduction by bacteria *(Desulfovibrio* spp, *Desulfotomaculum* spp and *Desulfuromonas* spp) is common in anaerobic conditions (Ehrlich, 1981). Its possible importance to inception in the pre-folding Madison Limestone, cannot be disregarded, particularly as dissolved hydrogen sulphide is itself acidic. Microbial reduction (or equivalent inorganic reactions) in the 'pre-cave' rock mass is unconfirmed, but with physical dissolution of evaporites as the only alternative, the possibility must be noted. Hydrogen sulphide generation in the anaerobic deep phreatic zone after inception is a still more attractive possibility .

Cave formation in travertine

Studies in the Banff National Park, Canada, led to recognition of an unusual example of sulphuric acid speleogenesis. Van Everingden and others (1985) described cave formation due to travertine corrosion by airborne sulphuric acid. This process was not linked into a more general consideration of speleogenesis, but the chemistry described, if not the actual development mechanism, is similar to ideas developed by Egemeier (1981). Dissolved sulphates are reduced by bacteria to form hydrogen sulphide in solution. Gaseous hydrogen sulphide escapes from the water surface and is oxidised and hydrolysed to produce sulphuric acid and sulphur dioxide. The airborne acid attacks calcium carbonate to produce calcium sulphate and carbon dioxide. Much of the authors' reasoning involved detailed study of oxygen and sulphur isotopes in various components (Figure 1). This allowed them to state, with reasonable certainty, that airborne acid fallout is currently involved in dissolving exposed carbonate, and the dissolved calcium sulphate, upon which the process depends, originated as primary marine evaporite. From the present viewpoint the conditions and type of speleogenesis encountered at this locality must be considered a special case, but similar chemistry, with or without microbial mediation, may be more widely applicable. Sulphate occurs, even if only in trace quantities, in most marine limestones. More sulphate is expected in parts of carbonate successions deposited under the hypersaline conditions commonly associated with cycle boundaries *(sensu lato)* or, more locally, in lagoons, isolated from marine influence by reefs or sand bars. Such deposits, perhaps containing only limited evaporite, probably occur in most carbonate sequences. In the speleo-inception context, traces of 'impurity' provide atypical chemistry at inception horizons. The mechanism described by Van Everingden and others, utilizing strong acid derived from sulphate rather than from sulphide, may be viable at these stratigraphical levels.

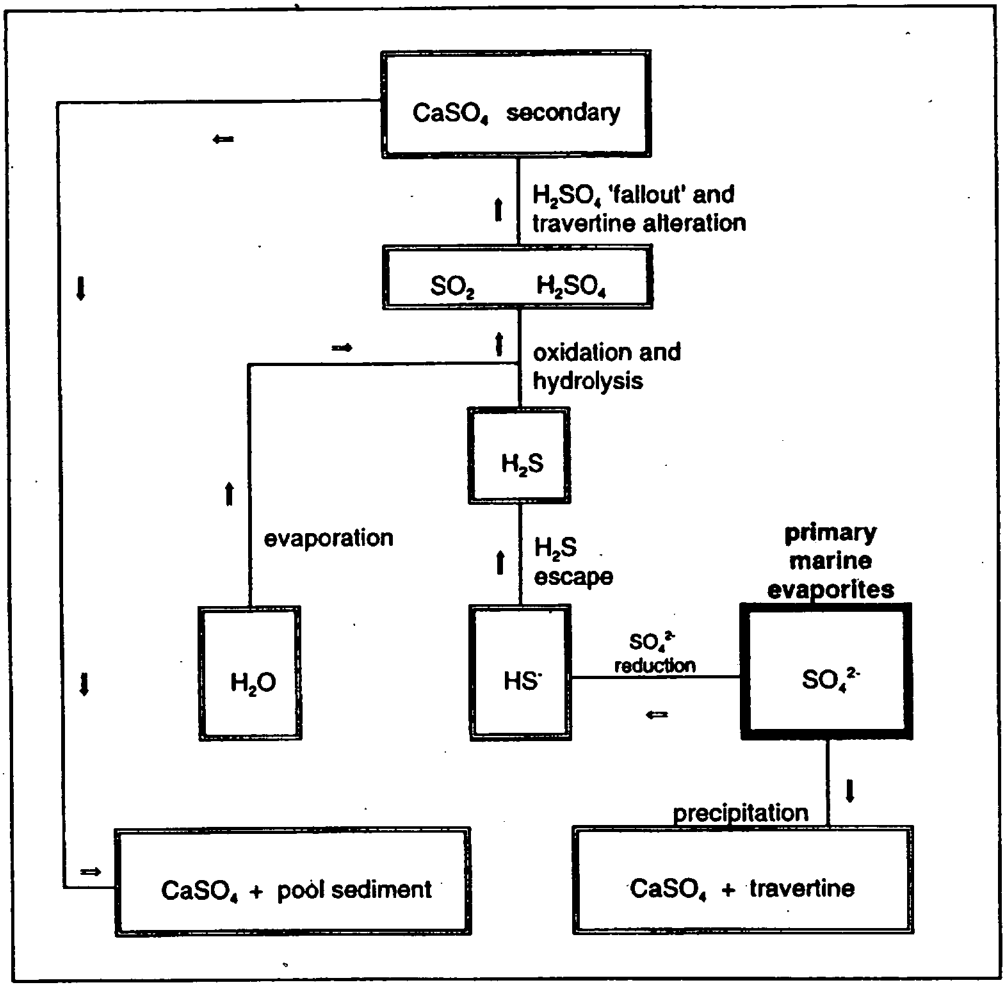

Figure 1 *Diagramatic representation of the interactions involved in fallout dissolution. Primary marine evaporites provide the starting point for the processes* (after Van Everingden and others, 1985)

Another cave in Quaternary travertine, Cesspool Cave in Virginia, owes its development to hydrogen sulphide hydration and oxidation and carbon dioxide hydration (Hubbard, Herman and Bell, 1986). Water entering the cave contains hydrogen sulphide, some of which is oxidised, probably partly by colourless bacteria (eg *Thiothrix* sp, *Beggiatoa* sp and *Achromatium* sp) in the cave water, to produce sulphuric acid via a sulphur intermediary:

$$2H_2S_{(aq)} + O_{2(aq)} \Rightarrow 2S^0_{(s)} + H_2O$$

$$2S^0_{(s)} + 3O_{2(aq)} + 2H_2O \Rightarrow 4H^+ + 2SO_4^{2-}$$

Hydrogen sulphide outgassing from cave water redissolves in film water on cave ceiling and walls and is oxidised by dissolved oxygen. Dissolution of wall and ceiling calcite proceeds in parallel with gypsum precipitation. The mechanism is identical to that proposed by Egemeier (1973, 1981) and replicates part of that deduced by Van Everingden and others (1985) for *"fallout"* dissolution. Three possible sources for the hydrogen sulphide are suggested. Local spring water shows high sulphate concentrations, and bacterial reduction of sulphate to sulphide could occur in the subsurface water supply. The travertine is underlain by black shales containing metastable iron minerals such as greigite (Fe_3S_4) and mackinawite (FeS) that can decompose to generate hydrogen sulphide. Finally, hydrogen sulphide could be derived from hydrocarbons in the black shale or adjacent Helderberg Limestone, the gas moving up dip to the cave area.

Caves in the Guadalupe Mountains, New Mexico

A major publication (Hill, 1987) describing cave development in the Capitan Reef of the Guadalupe Mountains, New Mexico consolidated ideas from earlier short papers (Hill, 1981, 1985, 1986). A multistage history of speleogenesis was described, including a major phase of dissolution due to sulphuric acid, by a mechanism previously proposed by D.G. Davis (1979, 1981) and resembling that described by Egemeier (above). Within a history that included three stages of dissolution, Hill considered that only Stage III was dominated to sulphuric acid, formed from hydrogen sulphide derived biogenically from hydrocarbon deposits in the adjacent Delaware Basin. The suggested reactions are:

1. $CaSO_4 + CH_4 \Rightarrow H_2S + CaCO_3 + H_2O$ [Delaware Basin]

2. $2H^+ + SO_4^{2-} + CH_4 \Rightarrow H_2S + CO_2 + H_2O$ [Delaware Basin]

3. $2H_2S_{(aq)} + O_{2(aq)} \Rightarrow 2S_{(s)} + 2H_2O_{(l)}$

4. $2H_2O_{(l)} + 2S_{(s)} + 3O_{2(aq)} \Rightarrow 2HSO_4^-{}_{(aq)} + 2H^+_{(aq)}$

5. $2H^+ + SO_4^{2-} + CaCO_3 + 2H_2O \Rightarrow CaSO_4.2H_2O + H_2O + CO_2$

Hill's basic model for these processes is very well supported by analytical results and by observations in the caves and has been further developed in subsequent papers (eg Hill 1990, 1995). As Hill stated (1995, p.16): *"The Delaware Basin....is probably the best example of sulfuric acid karst anywhere in the world."*. However, the Hill model for sulphuric acid speleogenesis during Stage III relies to some degree upon earlier speleogenetic activity in Stages I and II, deduced by Hill (1987) to have commenced soon after deposition and diagenesis of the Capitan Reef and associated fore- and backreef deposits during the Permian. In contrast to the 'special' case of the Stage III sulphuric acid dissolution, Hill's explanation of the earlier stages relies upon more traditional ideas of speleogenesis, in particular upon the Ford-Ewers (1978) model.

We have no first-hand knowledge of the Guadalupe caves, but would make several related points in the context of Hill's research and earlier cave development models proposed for the area. Firstly we suggest that in a speleogenetic history that began soon after the deposition of the host rocks in a reefal environment, the probable development and preservation of conduit permeability by dissolution adjacent to a contemporary freshwater lens cannot be ignored. If accepted, it must also be accepted that a proportion of open or loosely-filled conduits would survive subsequent uplift, stacked at several levels, as described in the Trobriand Islands (Ollier, 1975) and Tonga (Lowe, 1989). Such conduits would provide preferred sites for later underground drainage and dissolution. Secondly, if the presence and preservation of stacked conduits is accepted then much of the argument for bathyphreatic flow based on the Ford-Ewers model is no longer necessary. Relationships between conduits in the forereef area and those in the stacked backreef deposits are potentially analogous to those observed in the reef hinterland of 'Eua Island, Tonga (Lowe and Gunn, 1986). Following from this, a possibility emerges that secondary conduit enlargement (Hill's Stage II) could be partly due to dissolution by sulphuric acid derived from the backreef Yates Formation, as suggested by Jagnow (1977) but dismissed by Hill as inadequate to have caused the Stage III passage growth.

INDIRECT EVIDENCE FOR THE ROLE OF STRONG ACIDS IN SPELEOGENESIS

Many authors noted 'in passing' the potential involvement of strong acid in speleogenesis; in this section we consider indirect evidence and ideas crucial to the theme of this paper.

Sulphates in Castleguard Cave

Chemical studies by Yonge and Krouse (1987) indicate a link between sulphur-bearing compounds and carbonate speleogenesis. Samples of gypsum, mirabilite (hydrated sodium sulphate, $Na_2SO_4.10H_2O$), adjacent carbonate bedrock and cave water were collected from Castleguard Cave in the Canadian Rocky Mountains. Water of crystallization (from the minerals) and the cave water samples were analyzed for deuterium and oxygen-18. The two mineral species were analyzed to determine sulphur and oxygen isotope ratios, and bedrock samples were analyzed for trace sulphur species, using the method of Ueda and Sakai (1983). One of the formations analyzed, the Eldon Formation, was also studied by Gillott (1978; discussed below). Most sulphates in Castleguard Cave derive from sulphides in the host carbonates via pyrite oxidation (Yonge and Krouse, 1987); a minor proportion may derive directly from anhydrite in the rock mass. Discussing the acid forming process, Yonge and Krouse pointed out that each mole of oxidized pyrite can evolve 2 moles of sulphuric acid and that this reacts almost immediately with adjacent carbonate to produce sulphates and carbon dioxide that can dissolve to form another 2 moles of carbonic acid. They concluded that, *"The oxidation of pyrite as a source of the cave sulphates thus seems a likely mechanism in view of the isotopic and chemical evidence."* (Yonge and Krouse, 1987, p.429).

Sulphates in Indiana spring waters

Hydrochemical and isotopic studies of spring waters by Krothe and Libra (1983) provided unequivocal quantitative pointers to the role of strong acid in speleo-inception in southern Indiana, where Pennsylvanian rocks overlie a Mississippian, mainly carbonate, sequence. The uppermost Mississippian formations are more varied lithologically than those below, probably resembling cyclothemic sequences of similar age in northern England. Underlying beds are more massive, particularly the St Louis Formation, similar to many Asbian and Holkerian rocks in Britain. The St Louis Formation contains economic quantities of evaporite, the aspect of which passes from being interbedded, where preserved at depth, to occurring only as nodules closer to outcrop. Horizons that are highly evaporitic at depth are represented by brecciated rock at outcrop. Krothe and Libra deduced the presence of two flow systems. A shallow system carries meteoric water entering the system through open fractures and passing through traditionally and anthropocentrically defined cave passages; other waters utilize a deep, regional, system, recharged mainly by diffuse flow. Ion concentrations in the shallow system are highly variable; carbonic acid dissolution of calcite is the dominant process. Deep flow is characterized by limited ion concentration variation and high sulphate levels. A dissolution/precipitation interaction involving calcite, dolomite and gypsum dominates.

A possibility that currently observable 'shallow' systems elsewhere were conceived under conditions typical of Krothe and Libra's deep system cannot be ignored. Deep speleo-inception can begin before host carbonates are unroofed and before surface evolution provides viable conditions for 'normal' hydraulic flow. Evaporites occur within many deeply buried carbonate successions. After exhumation, the highest elements of incipient deep flow would transform into shallow flow systems, under conditions more normally associated with underground drainage. Early in the transformation residual evaporite would be removed from the rock mass, by speleogenesis *(sensu lato)* and by near surface weathering. Such changes explain the evaporite distribution in buried and outcrop elements of the St Louis Formation and may explain a lack of sulphate in near-outcrop shallow flow near recharge areas around the Big Horn Basin (Egemeier (1981; discussed above).

Sulphates in the English Dinantian

Tables 1 and *2* show extracts from whole rock analyses of major Dinantian formations in the Buxton and Settle areas, England. Most analyses are of unweathered borehole material, randomly sampled from each formation, rather than chosen to illustrate chemistry at different levels within depositional cycles. The values are for total sulphur content, expressed as SO_3 and therefore include sulphide as well as sulphate content. The values give a broad indication of sulphide/sulphate levels across typical Dinantian sequences.

Formation	Maximum SO_3 (%)	Minimum SO_3 (%)	Mean SO_3 %
Eyam Limestone	0.14	0.13	---
Monsal Dale Limestone	0.33	0.04	0.16
BEE LOW LIMESTONE			
Apron-reef facies	0.33	0.04	0.09
Miller's Dale Limestone	0.29	0.03	0.13
Chee Tor Rock	0.83	0.00	0.18
Undifferentiated	0.67	0.00	0.18
Woodale Limestone	0.62	0.00	0.17

Table 1 *SO_3 content (see text for explantation) of the major carbonate units in the Buxton area, Derbyshire, England* (after Harrison, 1981)

Additional information is provided by a deep borehole at Eyam in the Derbyshire Peak District (Dunham, 1973), which proved interbedded and disseminated anhydrite in deeply buried early Dinantian carbonates. The beds, which include crystals of calcium sulphate and calcite pseudomorphs after anhydrite, do not reach outcrop. It cannot be confirmed that exhumation and speleogenesis/weathering would remove evaporite, but T D Ford (1977) suggested that early groundwater movement could remove anhydrite, leading to increased permeability in the carbonate mass. Whether later Dinantian rocks at outcrop in Derbyshire included primary evaporites, deposited under sabhka conditions (Dunham, 1973) or as regressive elements of carbonate depositional cycles, is unknown. Little evidence of evaporites is recorded, yet widespread 'autobreccias' in the sequence could reflect evaporite removal, as described by Krothe and Libra (1983) in Indiana (discussed above). We suggest that primary evaporite is rarely preserved in relatively small outcrop and shallow subcrop areas, especially those of anticlinal aspect, such as those in the United Kingdom, due to dissolution. Only in zones of deep burial, such as proved at Eyam, or in much more extensive terrains, such as the Big Horn Basin and other North American examples, will evaporites survive uplift and dissolution across extended timespans.

Formation	Maximum SO_3 (%)	Minimum SO_3 (%)	Mean SO_3 %
Unspecified dolomitesed rocks	0.97	0.00	0.20
WENSLEYDALE GROUP			
Hardraw Scar Limestone	0.81	0.09	0.37
Grirvanella Beds, Upper Hawes Limestone and Gayle Limestone	0.95	0.07	0.38
Lower Hawes Limestone	1.45	0.04	0.23
MALHAM FORMATION			
Gordale Limestone	0.59	0.01	0.06
Cove Limestone	0.31	0.00	0.02
KILNSEY LIMESTONE			
Kilnsey Limestone	0.25	0.03	0.10
Kilnsey Limestone with Mudstone	1.42	0.21	0.74

Table 2 *SO_3 content (see text for explantation) of the major carbonate units in the Settle/Malham area, Yorkshire, England* (after Murray, 1983)

Exposure of limestone to coal leachates

Helz and others (1987) examined deleterious effects of coal leachates on the environment, confirming that: *"When coal is exposed to atmospheric precipitation, strongly acidic leachates....are produced."* (Helz and others, 1987, p.427) and: *"These leachates....tend to be more acidic than acid mine drainage."* (Helz and others, 1987, p.427). The main acid source was identified as oxidation of pyrite, catalyzed by bacteria. *Thiobacillus ferrooxidans* oxidizes ferrous to ferric iron, following which ferric ions rapidly oxidize pyrite by an abiotic mechanism that regenerates ferrous ions, propagating an ongoing reaction cycle. Adding dolomitic limestone to the stockpiles completely changed the leachate character, producing neutral solutions dominated by Ca^{2+}, Mg^{2+} and SO_4^{2-} ions, with the sulphate yield controlled by gypsum solubility. These reactions are potentially analogous to those active at lithological junctions between sulphurous coal (or shale) and carbonate rocks and calcium and magnesium sulphates rather than iron compounds dominated the leachate. Similar reactions proceed, more slowly, in less oxygenated conditions and at lower temperatures. The results confirm a commonplace chemical (and/or biochemical) mechanism, and provide several ancillary observations. Acid production in anoxic conditions is partially confirmed by observation that significant oxidation had occurred in fresh coal sampled at the mine, but whether this occurred *in situ* or when the coal was mined was not reported. The former possibility has far-reaching implications to speleogenesis; implications of the latter are only marginally less important. Acid generation in coal adjacent to voids or in contact with oxygenated groundwater in fracture zones appears inevitable rather than aberrant. Similar processes probably affect sulphurous rocks such as shale, mudstone and pyritic limestone.

In essentially carbonate-free conditions, distilled water passed through a coal stockpile acquired a pH of 3.2, decreasing gradually over 40 days to 1.8, then rising to 1.9 after 70 days. When 25% of dolomitic limestone was added to the stockpile acidic solutions were neutralised *in situ*. Starting at pH 7 the leachates were pH 6.4 after 14 days, dropping to 6.0 after 98 days, probably reflecting carbonate exhaustion. It is impossible to compare the effects of this 'strong acid' directly with the effects of carbonic acid, but clearly the sulphuric acid generated is a highly efficient remover of calcium (and magnesium) carbonate. Sulphuric acid generated *in-situ* removed carbonates forming 25% of the total solids in the stockpile in 98 days. Even if the test coal was exceptionally sulphurous and produced anomalously large volumes of acid, similar processes in less sulphurous coals or pyritic shales could produce less spectacular yet important speleogenetic effects. Carbonate sequences of different ages in different settings include, or lie adjacent to, beds of pyrite-rich shale, pyritic volcanic fallout or, more rarely, coal seams. If even a small proportion of their pyrite (or other sulphides) is oxidized to sulphuric acid, notable speleogenetic impact must be expected. Results from Vear and Curtis (below) confirm that significant volumes of sulphuric acid form even in slightly pyritic shales, and that this achieves appreciable carbonate dissolution. Such results, examined with so-called *'special cases'* (reviewed above), underline the potential importance of sulphuric acid, particularly to inception processes.

Chemical reactions in interbedded pyritic mudstones and carbonates

Two 'disasters' occurred during construction of the Carsington Dam and its associated aqueduct in Derbyshire, UK. In one incident workmen were asphyxiated by unexpectedly high carbon dioxide levels in a tunnel. In the second, less tragic, incident the dam collapsed. Subsequent detailed study of the geology, geomorphology and geochemistry near the dam was undertaken by the British Geological Survey (Aitkenhead and others, 1984), who concluded that the two incidents were potentially linked. The common factor was carbon dioxide, generated in undisturbed bedrock and, more critically, within compacted Namurian mudstone and limestone chippings comprising the dam body and drainage blankets. Carbon dioxide levels in gas drawn from the dam were far higher than expected. After heavy rain the carbon dioxide concentration tended to rise, and that of oxygen to fall. Fluctuation was irregular and extreme values of more than 60% carbon dioxide and less than 1% oxygen were recorded. In an area of soil overlying bedrock, readings before rain were 0.52% carbon dioxide and 20% oxygen compared to levels of 3.5% and 17% after rain. Similar fluctuation occurred in disturbed or undisturbed ground, but disturbed ground values were more extreme. Gas bubbles rising through a water filled trench in a borrow pit included 8% carbon dioxide and negligible oxygen. Reactions within the dam were depleting oxygen and generating carbon dioxide. Relatively small volumes of carbon dioxide formed under equilibrium-weathering conditions in undisturbed rock are significant in the context of the present paper.

Highly weathered mudstone, overlain by shallow water, in a borrow pit contained up to 6% soluble sulphate and visible efflorescence indicated that mobile sulphates were common in the pit. Limestone drainage layers showed extensive alteration to gypsum and epsomite. Aitkenhead and others (1984) deduced complex oxidation of sulphide-bearing mudstones, involving some microbial mediation, the products including carbon dioxide and sulphuric acid. The latter immediately attacks adjacent rock to generate more carbon dioxide and dissolve other minerals, profoundly changing the rock, physically and chemically. Suggested carbon dioxide production mechanisms are: 1. Bacterial oxidation of sulphide to sulphate generates carbon dioxide as a metabolic by-product; 2. Acidic sulphate solutions react with disseminated or interbedded carbonate, or with the limestone drainage blankets; 3. Oxidation of organic matter within mudstones and carbonates. [This was not considered important in the Carsington context]. Mechanisms 1. and 2. generated at least 80% of the carbon dioxide produced in the disturbed materials of the dam. The processes deduced by Aitkenhead and others (1984) are illustrated in simplified form in *Figure 2*.

Work by Pye and Miller (1990) further explored chemical reactions in pyritic mudstones and interbedded carbonates. Their study included laboratory simulation of conditions established during embankment construction; overall the results agree closely with those of Aitkenhead and others (1984) and Vear and Curtis (1981). Several aspects are relevant to speleo-inception and the reaction chain deduced differs in detail from mechanisms discussed elsewhere in this paper. Elements of Pye and Miller's work crucial to speleogenesis are condensed in one paragraph: "*...dilute sulphuric acid with an initial pH of 1.8 could dissolve virtually all the calcite present in the test specimens of Namurian marine mudstone within a period of two weeks. Dissolution of siderite and dolomite (where present) occurred at a slower rate. Carbonate dissolution can occur under either saturated or free-draining conditions, but in the field high rates of dissolution are likely to be favoured by a high acid flux. Under stagnant pore water conditions the rate of dissolution will be dependent primarily on the rate of ionic diffusion through the pore fluid.*" (Pye and Miller, 1990, p.378). The last sentence is particularly valuable, implying that oxidation and dissolution occur in situations where hydraulic flow would not be expected. The Inception Horizon Hypothesis (Lowe, 1992) assumes such motion as instrumental in the inception of primary voids in deep phreatic environments, remote from a surface landscape.

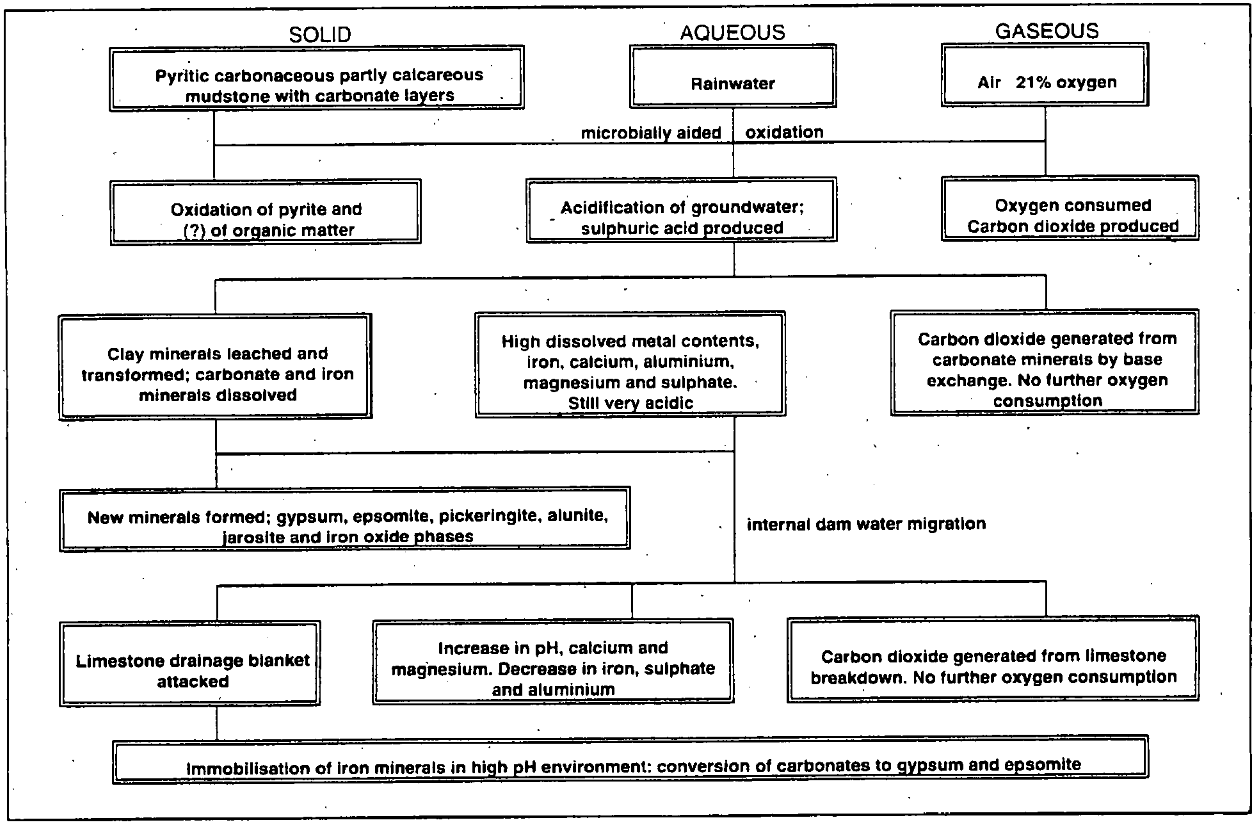

Figure 2 *Organogram of chemical changes associated with the breakdown of Namurian mudstones (with minor carbonates) in the Carsington area* (after Aitkenhead and others, 1984)

The dissolution rates described are of great importance. We consider that changes achieved rapidly under 'favourable' conditions can equally well be accomplished by similar processes acting under less favourable conditions during the far longer timespans of speleogenesis. The more important reactions listed by Pye and Miller (1990) are:

1. Pyrite dissolution in the presence of dissolved oxygen, forms ferrous sulphate and sulphuric acid:

   $FeS_2 + H_2O + 7O \Rightarrow FeSO_4 + H_2SO_4$

2. Ferrous sulphate reacts with oxygen and sulphuric acid, forming ferric sulphate:

   $2FeSO_4 + O + H_2SO_4 \Rightarrow Fe_2(SO_4)_3 + H_2O$
   [This may be catalysed by *Thiobacillus* spp.]

3. Ferric sulphate, a powerful oxidizing agent, can react with pyrite, producing ferrous sulphate and elemental sulphur:

   $Fe_2(SO_4)_3 + FeS_2 \Rightarrow 3FeSO_4 + 2S$

4. Elemental sulphur in the presence of water and oxygen is converted to sulphuric acid, catalysed by *Thiobacillus ferrooxidans*:

   $S + 3O + H_2O \Rightarrow H_2SO_4$

5. If free oxygen is abundant, aqueous oxidation of pyrite produces ferric hydroxide and sulphuric acid:

   $FeS_2 + 15/4O_2 + 7/2H_2O \Rightarrow Fe(OH)_3 + 2H_2SO_4$

Groundwater chemistry in Namurian rocks at Mam Tor, Derbyshire

Studying groundwater chemistry in Namurian rocks at Mam Tor, Derbyshire, Vear and Curtis (1981) demonstrated that shale pyrite was oxidising, producing sulphuric acid at an unprecedented rate. Oxygenated groundwater along a fault crush zone was breaking down 1.5g of pyrite per litre of water. More than 99% of the acid was consumed by clay-mineral transformations and carbonate dissolution. Many carbonate successions include pyritic clastic beds, coal seams or volcanic deposits, and dark carbonates adjacent to shale beds or in analogous positions represented by palaeokarstic surfaces are commonly pyritic. Groundwater within clastic rocks is not *'oxygenated'* in the same sense as a fast-flowing stream, but it holds dissolved oxygen. Except for the host rock lithology, this water is analogous to shallow, oxygenated, phreatic zone water (cf Ball and Jones, 1990, figure 4) or *'vadose seeps'* (Thrailkill, 1968) in carbonate aquifers. It appears unequivocal that sulphuric acid must form where pyrite-rich rocks are traversed by active shallow phreatic or vadose flow (cf Krothe and Libra (1983) discussed above).

Vear and Curtis analyzed what they term as *'karst'* water from Peak Cavern resurgence. However, the actual sampling site was Peakshole Water downstream of the three resurgences which drain the Peak-Speedwell Cave System. Two of these, Slop Moll and Russet Well, receive significant allogenic recharge from streams sinking below Rushup Edge, west of Mam Tor while the third, the true Peak Cavern resurgence, is supplied solely by autogenic recharge from the limestone outcrop during normal conditions but functions as a flood overflow for the allogenic system (Gunn, 1991). In the allogenic catchment, precipitation, and drainage from minor springs on Namurian rocks similar to those of Mam Tor, descend an input system explored to a depth of 160 m, but with no passable link to the resurgences. Most of the flow must follow deep phreatic routes along joints, faults and veins (Ford, 1986). Over a ten-week sampling period Vear and Curtis found that the resurgent water chemistry responded relatively little to rainfall events. Fault crush zone drainage on Mam Tor showed a similar lack of chemical variation, though the overall chemistry was dissimilar. The similar behaviour suggests relatively lengthy residence times at depth for both waters although water tracing indicates more rapid flow-through times for the allogenic waters. Samples from surface runoff, shallow seepage and springs unrelated to the fault crush showed appreciable temporal variation. Many radicals included in Vear and Curtis's analyses (1981, p.193) are not relevant here, but selected figures (*Table 3*) are of interest.

Type of drainage	Calcium	Magnesium	Ferrous+ Ferric	Sulphate	pH
Surface runoff	21.0	7.9	3.0	105.0	5.2
Peak Cavern	78.0	2.9	2.6	90.0	6.4
Fault crush zone	385.0	178.0	111.0	2362.0	3.4
Mixture of surface and fault crush zone drainage	199.0	88.0	98.0	1156.0	3.2

Table 3 *Mean values of selected radicals (micrograms per millimetere) and pH from four types of water sampled during an eight-week period.*
Note that the Peak Cavern samples were collected from Peakshole Water and include flows from Slop Moll and Russet Well. (after Vear and Curtis, 1981, Table II, p. 193)

The pH of the Peakshole Water drainage is as expected in view of the projected residence times and the ready supply of calcium carbonate along the flow route to neutralise acids carried into the system or generated underground. The pH and sulphate content of fault crush zone and karst waters present an interesting comparison, suggesting dilution effects and swamping by other processes. We assume that low calcium (and ?magnesium) values also mirror dilution within the bulk flow from the Peak-Speedwell system. The difference between the magnesium figures from the surface runoff and Peakshole Water analyses suggest an effective three-times dilution in the cave environment, though an obvious disparity of calcium values between the same two sets of analyses remains, due to environment differences.

The pyrite decomposition mechanism suggested by Vear and Curtis resembles that proposed by Helz and others (1987, discussed above), the overall reaction being:

$$FeS_2 + 14Fe^{3+} + 8H_2O \Rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$

In near surface environments this is complemented by ferrous to ferric iron oxidation catalysed by *Thiobacillus ferrooxidans*:

$$4Fe^{2+} + O_2 + 4H^+ \Rightarrow 4Fe^{3+} + 2H_2O$$

Vear and Curtis suggested that the process is best described by two end-member reactions depending upon the degree of ferrous oxidation:

$$2FeS_2 + 14(O) + 2H_2O \Rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+$$
$$2FeS_2 + 15(O) + H_2O \Rightarrow 2Fe^{3+} + 4SO_4^{2-} + 2H^+$$

However, they also noted that the formulations fail to explain the full evolution of the waters analyzed, and discussed other processes, including hydrated ferric oxide precipiation, clay mineral alterations and carbonate dissolution. For every 1.4996g of pyrite destroyed, potentially 1.5684g of dolomite dissolves and 1.221g of limonite precipitates. If the products are removed by percolating water a *"massive increase in porosity"* (Vear and Curtis, 1981, p.196) occurs. Overall, Vear and Curtis concluded that the scale of chemical alteration is very great. More than 99% of the sulphuric acid formed at depth is consumed by silicate and carbonate reactions before reaching the surface. Of this 99%, 77% is involved in carbonate dissolution. These findings are potentially significant to speleogenesis. Figures deduced for sulphuric acid production in oxygenated phreatic environments indicate that, in some geological and hydrological conditions met in the context of speleogenesis, sulphuric acid could have great effect.

The effect of deicing agents and sulphate solutions on concrete aggregate

Although apparently unrelated to speleogenesis, evidence presented by Gillott (1978) indicates that factors other than acidic dissolution might play a previously unrecognised part in karst processes *(sensu lato)*. Gillott studied quartzitic and carbonate aggregates, the carbonates ranging from almost pure dolomite to almost pure calcite. Measured rock cylinders were immersed in distilled water (as control) and in solutions of

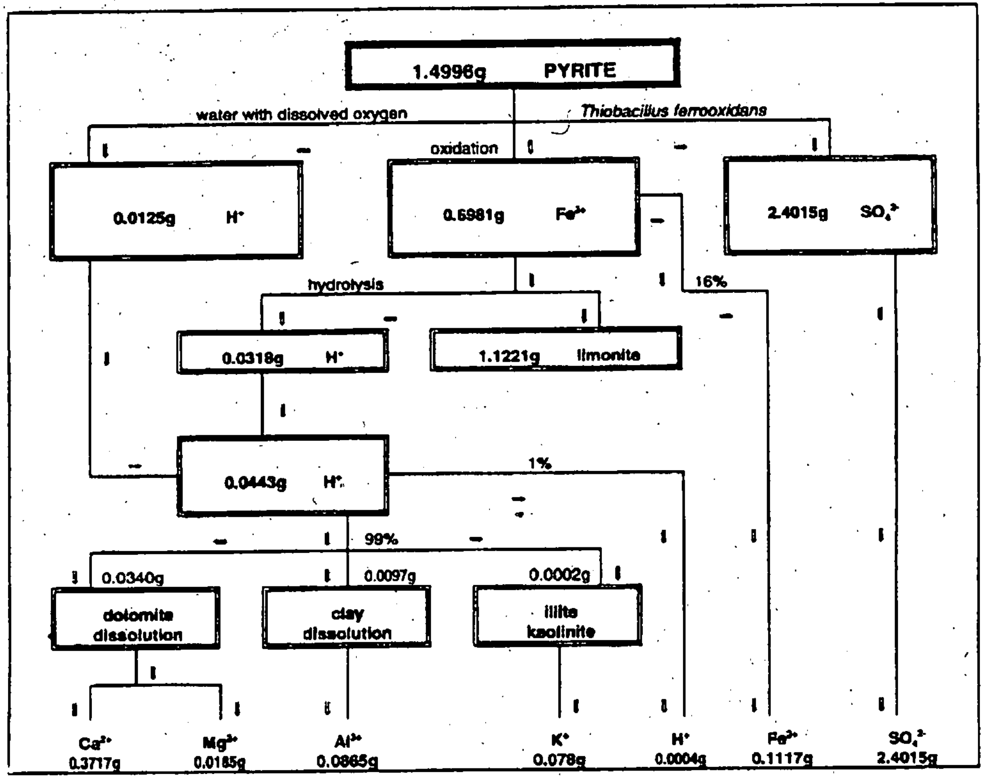

Figure 3 Chemical reactions affecting the water from a fault crush zone spring. Amounts shown refer to changes affected by the passage of 1 litre of water and the values balance when account is taken of molecular weights (after Vear and Curtis, 1981).

sodium and calcium chlorides (5% and saturated) and magnesium sulphate (4% and saturated) at a constant 20 °C. All cylinders were soaked in water for a week before testing, to ensure saturation of open pores, and were remeasured after three days and seven days, at weekly intervals for a month, and every month for more than two years. A broad picture of dimensional change emerged, related to carbonate lithology and salt solution chemistry/concentration. Samples of Eldon Limestone (calcite with minor dolomite) showed a dimensional decrease of 0.12% after immersion in saturated magnesium sulphate solution. This apparently trivial decrease is sufficient to allow the removal by sulphate action of 1.2mm in every 1m of carbonate, if the effects were concentrated along a bedding plane or joint. Gillott examined immersed carbonates using a scanning electron microscope. Most effects observed involved dissolutional removal of carbonate, plus or minus scaling off of crystalline sheets; a few involved deposition. Similar effects were noted on dolomitic and calcitic rocks.

Gillott's results, significant in a civil engineering context, also have a link to speleogenesis, suggesting that carbonate dissolution need not be due only to acids. If chloride and sulphate solutions cause dissolution in concrete aggregates, naturally occurring solutions could also affect porous or secondarily permeable carbonate bedrock. We suggest two potential situations. Sulphates and (less commonly) chlorides precipitate during regressive phases of cyclic carbonate deposition (eg Scoffin, 1987), and chlorides and other salts in sea-water are in contact with carbonate rocks in coastal situations. Some effects noted by Gillott relate to visible cleavage within the carbonate mineral fabric. Calcite's molecular/crystal structure presents a perfect cleavage on the microscopic scale, but it is unclear whether these planes are significant, or whether only the coarser, visible cleavage fabric is involved. If the latter, dissolution should be more marked where sulphate- and/or chloride-rich solutions can attack coarse, readily cleavable, crystalline rocks. 'Sparry limestone' should be more susceptible than 'micritic' rocks and shell-rich beds could be especially implicated. In regressive parts of 'perfect' depositional cycles, sulphate- and chloride-rich sediments and shelly build-ups occur close to superimposed 'sparry' carbonates. The potential links between hypersaline deposition, shell beds and secondary porosity due to dissolution of evaporites or their reaction with carbonate require further investigation.

Processes including evaporite dissolution and the effects of 'salt solutions' in corroding carbonates are deduced to affect cave inception in suitable environments. Subsidence into cavities in gypsum (eg Cooper, 1986) demonstrates that dissolution occurs deep in buried sequences with no initial potential for direct flow to surface risings and no viable hydraulic gradient, both seen by many workers as essential to trigger underground drainage and speleogenesis. Evidence from many fields supports the view that non-traditional dissolution occurs in buried rocks before surface downcutting establishes resurgences and local hydraulic gradients.

Microbial activity

Ehrlich (1981) described many bio-chemical interactions that may potentially affect speleogenesis. The full extent of Ehrlich's work cannot be examined here, but three basic reactions and their implications are summarized. Similar reactions, if not the microbial mediation, are discussed elsewhere in this paper, but the variety of organisms potentially involved is of interest:

a. Sulphide oxidation to elemental sulphur, mediated by:
   - *Thiobacillus* spp
   - Purple sulphur bacteria
   - Green sulphur bacteria
   - Cyanobacteria
   - *Beggiatoa* spp

b. Oxidation of elemental sulphur to sulphuric acid, mediated by:
   - *Thiobacillus* spp
   - *Sulfolobus* spp

c. Reduction of sulphates to hydrogen sulphide, mediated by:
   - *Desulfovibrio* spp
   - *Desulfotomaculum* spp
   - *Desulfuromonas* spp

Ehrlich also noted that elemental sulphur may be reduced to hydrogen sulphide by bacteria such as *Desulfuromonas acetoxidans*, in anaerobic conditions. Many processes described are rationalised into equations equivalent to those reproduced in this paper. The following are potentially important to speleogenesis, but the list is not exhaustive:

$$S^{2-} + \tfrac{1}{2}O_2 + 2H^+ \Rightarrow S^0 + H_2O$$

$$2S^0 + 3O_2 + 2H_2O \Rightarrow 2H_2SO_4$$

$$FeS_2 + 7/2O_2 + H_2O \Rightarrow Fe^{2+} + 2H^+ + 2SO_4^{2-}$$

$$FeS_2 + 14Fe^{3+} + 8H_2O \Rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$

Ehrlich's equations to illustrate sulphate reduction reactions (Ehrlich, 1981, pp.263-265) comprise several steps, involving complex organic intermediaries, and are not repeated here. Optimum temperature and aeration conditions for bacterial activity described by Ehrlich indicate that organisms exist that can, and do, mediate in aerobic and anaerobic environments spanning the spectrum of hydrographic zones.

Reports by T.D. Ford (1965), of a link between microbial activity and rock breakdown were largely ignored, but the role of bacteria in speleogenesis, barely touched in the current paper, invites detailed study. Bottrell and others (1990) produced convincing evidence that acidity is generated by bacterial reduction of sulphates near the halocline at the base of the freshwater/saltwater mixing zone. The sulphur species are re-oxidised at shallower depths, providing sulphuric acid whose contribution to wall rock dissolution is at least as great as that of freshwater/saltwater mixing, itself a highly effective process with a clear and fundamental importance to speleogenesis. Bosch and others (1989), provided further insight of activity within coastal carbonate aquifers, where ion exchange (cf Gillott, 1978; discussed above) was shown as potentially important in carbonate dissolution below the vadose zone. All water samples were depleted in sulphate following reduction to hydrogen sulphide, giving further evidence for the potential involvement of reduced/re-oxidized sulphur compounds in early speleogenesis. These results provide a valuable link between conventional views of carbonate dissolution, the more recently recognized process of mixing zone corrosion and sulphuric acid dissolution.

CONCLUSION

In this paper we have attempted to illustrate and emphasise the importance of sulphuric acid, plus or minus other non-traditional processes, to early speleogenesis, while acknowledging that carbonic acid dissolution is volumetrically more significant during later stages. It is important to recognise that analytical data from mature cave systems may obscure evidence for the vital role of sulphuric acid in cave inception. Regrettably, but not surprisingly, most data are from mature systems and shallow flow springs and there are relatively few data from 'deep' flow systems. Analyses of 'deep' flows in Derbyshire, including *'thermal springs'* (Edmunds, 1971), showed sulphate levels as high as 384 mg/litre suggesting that speleogenesis by sulphuric acid and/or calcium sulphate dissolution may be dominant at depth. In this context it is interesting to note that the role of sulphur-related redox processes in deep karst processes has recently begun to be accepted (Palmer, 1995). In addition, Worthington (1991) suggested that much dissolution by *'underflow'* water is of calcium sulphate rather than calcium carbonate. This may indicate physical, dissolution of primary mineral in the rock mass, a potential inception horizon function, although Worthington suggested that sulphate could form *in situ* as a product of calcium carbonate dissolution by sulphuric acid. Much of Worthington's work was quantitative and his results underline the importance of strong acid dissolution, as deduced qualitatively and reported here. Worthington's recognition of the significance of calcium sulphate removal may be crucial to the future development of cave formational theories, but his ideas do not relate directly to inception horizons or other forms of chemical zonation in carbonate successions.

Increasing evidence points directly or indirectly to the importance of sulphuric acid in speleogenesis. We suggest that sulphuric acid dissolution, and other 'aberrant' mechanisms, affect all stages of speleogenesis, but their greatest importance, instrumentally and volumetrically, is during inception and the subsequent phase of laminar flow, prior to turbulent breakthrough, which we term gestation. We cannot yet show conclusively that speleogenesis would not proceed without these 'exotic' mechanisms, but point out that many unanswered questions in pre-existing cave development theories cease to present problems if the alternative processes are accepted. Much of our discussion concerns *'special cases'* of speleogenesis due to sulphuric acid dissolution. In the light of increasing evidence for more general involvement of sulphuric acid dissolution and related mechanisms, we consider that *'special cases'* are actually **extreme** cases of speleogenesis by processes not based exclusively upon carbonic acid.

Processes appearing quantitatively insignificant in post-gestational speleogenesis may have relatively great importance before establishment of turbulent conduit flow. During inception, strong acid dissolution appears vital, though the amount of carbonate dissolved is small. Traditional dissolutional processes do not operate initially, though they commence, due to *'doubled solvency'* effects (eg Ball and Jones, 1990), soon after inception. As gestation and turbulent flow development progress, the proportion of total conduit enlargement by strong acid generally decreases, but strong acid dissolution continues throughout the life of the conduit. Analyses of seepages from incipient inception horizons and discharges from deep phreatic systems, commonly confirm a dominance of sulphur-bearing ions as against carbonate and bicarbonate. Equally, as integrated drainage systems develop and hydraulic conductivity improves, relatively constant yields of sulphur-bearing ions are progressively overwhelmed by increasing production of carbonic acid reaction products. From this viewpoint the effect of 'exotic' acids is perceived as negligible - from the speleo-inception standpoint it is considerable and fundamental.

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REFERENCES

Aitkenhead, N, Riley, N J, Ball, T K, Nicholson, R A, Peachey, D, Bloodworth, A J, Rouse, J E, Miller, M F and Thrift, L, 1984. 'Carsington reservoir dam failure; geological, geomorphological and geochemical aspects of the site, final report'. *Report of the British Geological Survey.*

Ball, T K and Jones, J C, 1990. 'Speleogenesis in the limestone outcrop north of the South Wales Coalfield; the role of micro-organisms in the oxidation of sulphides and hydrocarbons'. *Cave Science*, **17**, 3-8.

Bosch, X, Custodio, E and Pascual, M, 1989. 'Geochemical reactions in carbonate coastal aquifers, Catalonia, Spain'. In Simpson, E S and Sharp, J M, (editors). *Selected papers on hydrogeology from the 28th International Geological Congress, Washington, USA, 1989,* pp 147-159

Bottrell, S H, Smart, P L, Whitaker, F and Raiswell, R, 1990. 'Geochemistry and isotope systematics of sulphur in the mixing zone of Bahamian blue holes'. *Applied Geochemistry*, **6**, 97-103.

Cooper, A H 1986. 'Subsidence and foundering of strata caused by the dissolution of Permian gypsum in the Ripon and Bedale areas, North Yorkshire'. In Harwood, G M and Smith, D B, (editors), *The English Zechstein and Related Topics. Geological Society Special Publication* No.22, pp 127-139

Davis, D G, 1979. 'Cave development in the Guadalupe Mountains, New Mexico, Texas'. *Caving International*, **3**, 43.

Davis, D G, 1980. 'Cave development in the Guadalupe Mountains: a critical review of recent hypotheses'. *National Speleological Society Bulletin*, **42**, 42-48.

Davis, W M, 1930. 'Origin of limestone caverns'. *Geological Society of America Bulletin*, **41**, 475-628.

Dunham, K C, 1973. 'A recent deep borehole near Eyam, Derbyshire'. *Nature: Physical Science*, **243**, 84-85.

Durov, S A, 1956. 'On the question about the origin of the salt composition of karst water'. *Ukrainian Chemical Journal*, **22**, 106-111. [English translation by Muller, O, 1979, in *Cave Geology*, **1**, 185-190.]

Edmunds, W M, 1971, 'Hydrogeochemistry of ground waters in the Derbyshire Dome with special reference to trace constituents'. *Report No. 71/7 of the Institute of Geological Sciences,* 52pp.

Egemeier, S J, 1973. *Cavern development by thermal waters with a possible bearing on ore deposition*. Thesis, Stanford University.

Egemeier, S J, 1981. 'Cavern development by thermal waters'. *National Speleological Society Bulletin*, **43**, 31-51.

Ehrlich, H L, 1981. *Geomicrobiology*. Marcel Dekker Inc, New York.

Ford, D C, and Ewers, R O, 1978. The development of limestone cave systems in the dimensions of length and depth' *Canadian Journal of Earth Sciences*, **15**, 1783-1798.

Ford, D C and Williams, P W, 1989. *Karst Geomorphology and Hydrology*, Unwin Hyman, London.

Ford, T D, 1965. 'An ultimate food source for cave life?'. *British Hypogean Fauns and Biological Records of the Cave Research Group of Great Britain,* No.1, 24-25.

Ford, T D, (Editor), 1977. *Limestones and Caves of the Peak District*, Geo Abstracts, Norwich.

Ford, T D, 1986. 'The evolution of the Castleton Cave Systems, Derbyshire'. *Cave Science*, **13**, 131-148.

Gardner, J H 1935. 'Origin and development of limestone caverns'. *Bulletin of the Geological Society of America*, **46**, 1255-1274.

Gillott, J E, 1978. 'Effect of deicing agents and sulphate solutions on concrete aggregate'. *Quarterly Journal of Engineering Geology*. **11**, 177-192.

Groves, C G and Howard, A D, 1994a. 'Minimum hydrochemical conditions allowing limestone cave development'. *Water Resources Research*, **30**, No.3, 607-615.

Groves, C G and Howard, A D, 1994b.'Early development of karst systems. 1. Preferential flow path enlargement under laminar flow'. *Water Resources Research*, **30** , No.10, 2837-2846.

Groves, C G and Howard, A D, 1995.'Early development of karst systems. 2. Turbulent flow'. *Water Resources Research*, **31** , No.1, 19-26.

Gunn, J, 1991.'Water-tracing experiments in the Castleton karst, 1950-1990'. *Cave Science*, **18**, No. 1, 43-46.

Harrison, D J, 1981. 'The limestone and dolomite resources of the country around Buxton, Derbyshire.. Description of 1:25000 sheet SK07 and parts of SK06 and 08'. *Mineral Assessment Report of the Institute of Geological Sciences* No.77.

Helz, G R, Dai, J H, Kijak, P J, Fendinger, N J, and Radway, J C, 1987. 'Processes controlling the composition of acid sulfate solutions evolved from coal'. *Applied Geochemistry*, **2**, 427-436.

Hill, C A, 1981. 'Speleogenesis of Carlsbad Caverns and other caves of the Guadalupe Mountains'. *Proceedings of the 8th International Speleological Congress*, Bowling Green, Kentucky, 143-144.

Hill, C A, 1985. 'Speleogenesis of Carlsbad Cavern and other caves of the Guadalupe Mountains, New Mexico'. *Newsletter of the National Speleological Society Section on cave geology and geography*, **12**, No.2, 30-31.

Hill, C A, 1986. 'Carlsbad Cavern and other caves in the Guadalupe Mountains, New Mexico: A sulphuric acid genesis related to the oil and gas fields of the Delaware basin'. *Proceedings of 9th International Speleological Congress*, Barcelona, **1**, 267-269.

Hill, C A, 1987. 'Geology of Carlsbad Cavern and other caves in the Guadalupe Mountains'. *New Mexico Bureau of Mines and Mineral Resources Bulletin* 117.

Hill, C A, 1990. 'Sulfuric acid speleogenesis of Carlsbad Caverns and its relationship to hydrocarbons, Delaware Basin, New Mexico and Texas'. *Bulletin of the American Association of Petroleum Geologists*, **74**(11), 1685-1694.

Hill, C A, 1995. 'Sulfur redox reactions: Hydrocarbons, native sulfur, Mississippi Valley-type deposits, and sulfuric acid karst in the Delaware Basin, New Mexico and Texas'. *Environmental Geology*, **25**, 16-23.

Howard, A D, 1960. 'Geology and origin of the crevice caves of the Iowa, Illinois and Wisconsin lead-zinc district'. *Journal of the Yale Speleological Society*, **2**, No.4, Part 1, 61-95.

Howard, A D, 1964. 'Processes of limestone cave development'. *International Journal of Speleology*, **1**, 47-60.

Hubbard, D A Jr, Herman, J S and Bell, P E, 1986. 'The role of sulphide oxidation in the genesis of Cesspool Cave, Virginia, USA'. *Proceedings of 9th International Speleological Congress*, Barcelona, **1**, 255-258.

Jagnow, D H, 1977. *Geologic factors influencing speleogenesis in the Capitan Reef Complex, New Mexico and Texas*. Unpublished MSc thesis, University of New Mexico.

Jakucs, L, 1977. *Morphogenetics of Karst Regions*, Adam Hilger, Bristol.

Kaye, C A, 1957. 'The effect of solvent motion on limestone solution'. *Journal of Geology*, **65**, 35-46.

Klimchouk A B, 1986. 'Genesis and development history of the large gypsum caves in the Western Ukraine'. *Le Grotte d'Italia*, **4(XII)**, 51-71.

Krothe, N C and Libra R D, 1983. 'Sulfur isotopes and hydrochemical variations in spring waters of southern Indiana, U.S.A'. *Journal of Hydrology*, **61**, 267-283.

Lowe, D J, 1989. *Tonga '87 - the Report of the 1987 speleological expedition to 'Eua Island, Kingdom of Tonga*. 28+ii pp, 18 figures, photographs. Private publication.

Lowe, D J, 1992. *The origin of limestone caverns: an inception horizon hypothesis*. Unpublished PhD Thesis, Manchester Metropolitan University/Council for National Academic Awards.

Lowe, D J and Gunn, J, 1986. 'Caves and limestones of the islands of Tongatapu and 'Eua, Kingdom of Tonga'. *Transactions of the British Cave Research Association*, **13**, 105-130.

Morehouse, D F, 1968. 'Cave development via the sulfuric acid reaction'. *National Speleological Society Bulletin*, **30**, 1-10.

Murray, D W, 1983. 'The limestone and dolomite resources of the country around Settle and Malham, North Yorkshire (with notes on the hard-rock resources of the Horton-in-Ribblesdale area). Description of parts of geological sheets 50 and 60'. *Mineral Assessment Report of the Institute of Geological Sciences*, No.126.

Ollier, C D, 1975. 'Coral island geomorphology - the Trobriand Islands'. *Zeitschrift für Geomorphologie*, **19**, 164-190.

Palmer, A N, 1995. 'Deep-seated geochemical environments in karst: An introduction'. *Environmental Geology*, **25**, 1.

Pye, K and Miller, J A, 1990. 'Chemical and biochemical weathering of pyritic mudrocks in a shale embankment'. *Quarterly Journal of Engineering Geology, London*, **23**, 365-381.

Queen, J M, 1973. 'Large scale replacement of carbonate by gypsum in some New Mexico caves (abstract)'. *National Speleological Society Convention, Bloomington, Indiana, Abstracts with programs*, p.12.

Queen, J M, Palmer, A N and Palmer, M V, 1977. 'Speleogenesis in the Guadalupe Mountains, New Mexico, gypsum replacement of carbonate by brine mixing'. *Proceedings of the Seventh International Speleological Congress, Sheffield, UK*. 333-336.

Sando, W J, 1988. 'Madison Limestone (Mississippian) paleokarst: a geologic synthesis'. In James, N P and Choquette, P W, (editors), *Paleokarst*, Springer Verlag, New York, pp 256-277.

Scoffin, T P, 1987. *An introduction to carbonate sediments and rocks,* Blackie, Glasgow and London.

Thrailkill, J V, 1968. 'Chemical and hydrologic factors in the excavation of limestone caves'. *Bulletin of the Geological Society of America*, **79**, 19-45.

Ueda, A and Sakai, H, 1983. 'Simultaneous determinations of the concentration and isotope ratio of sulfate- and sulfide-sulfur and carbonate-carbon in geological samples'. *Geochemical Journal*, **17**, 185-196.

Van Everingden, R O, Shakur, M A and Krouse, H R, 1985. 'Role of corrosion by H_2SO_4 fallout in cave development in a travertine deposit - evidence from sulfur and oxygen isotopes'. *Chemical Geology*, **49**, 205-211.

Vear, A and Curtis, C, 1981. 'A quantitative evaluation of pyrite weathering'. *Earth Surface Processes and Landforms*, **6**, 191-198.

Worthington, S R H, 1991. *Karst hydrogeology of the Canadian Rocky Mountains.* Unpublished PhD thesis, McMaster University.

Worthington, S R H and Ford, D C, 1995. 'High sulphate concentrations in limestone springs: An important factor in conduit initiation?'. *Environmental Geology,* **25**, 9-15.

Yonge, C J and Krouse, H R, 1987. 'The origin of sulphates in Castleguard Cave, Columbia Icefields, Canada'. *Chemical Geology (Isotope Geoscience Section)*, **65**, 427-433.

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MAJOR PROTECTED SITES OF LIMESTONE PAVEMENT IN GREAT BRITAIN

Helen S. GOLDIE

INTRODUCTION

Ten limestone pavement sites in Britain have been deemed to merit inclusion in the nation-wide Geological Conservation Review (GCR) of over 80 karst sites, as Sites of Special Scientific Interest (SSSI) for geological and geomorphological value. Some are also very valuable botanically.

All sites are in Northern England's two major karst areas, the Yorkshire Dales and North-West England (west of the Pennines) (see Fig. 1). Ingleborough, Scales Moor and Conistone Old Pasture are in the Yorkshire Dales National Park (YDNP), which includes the best-known karst areas of Britain. Three sites lie west of the YDNP in the karst areas fringing Morecambe Bay: Gaitbarrows is in the Arnside-Silverdale Area of Outstanding Natural Beauty (AONB), and Hutton Roof and Farleton Knott occupy a prominent mid-altitude hill nearby. Potts Valley, Great Asby Scar and The Clouds are north-west of the Yorkshire Dales. A tenth site, Helbeck Scars, first assigned SSSI status for its botany, is the only site on the Alston Block, the more northerly of the two North Pennine structural blocks.

These pavements are the best-known national sites and constitute a large proportion of the total British pavement area. There are, however, many other sites in England not afforded this level of conservation interest and the GCR excludes examples from Wales or Scotland, despite their value and interest.

This paper describes the nine major sites in some detail and discusses the important characteristics which have made them worthy of the highest conservation status for these landforms in the whole country. A botanical survey of Britain's limestone pavements (Ward & Evans, 1976) established the enormous merit of many sites, including these, on botanical criteria, and referred also to their geomorphology. This survey has been used extensively to support recent efforts to protect limestone pavement sites, particularly after the Wildlife and Countryside Act of 1981 provided arrangements for legal protection for these landforms. Under this Act a Limestone Pavement Order (LPO) can be made for a site, on which various activities are prevented. Transgressions are punishable with fines, although so far few have occurred. The simple status of SSSI does not provide this level of protection.

GEOLOGICAL BACKGROUND

Northern England has some of the best-developed and best-known karst areas of Britain. Some sites are little known as karst, such as The Clouds, while others are internationally known, such as the Ingleborough area.

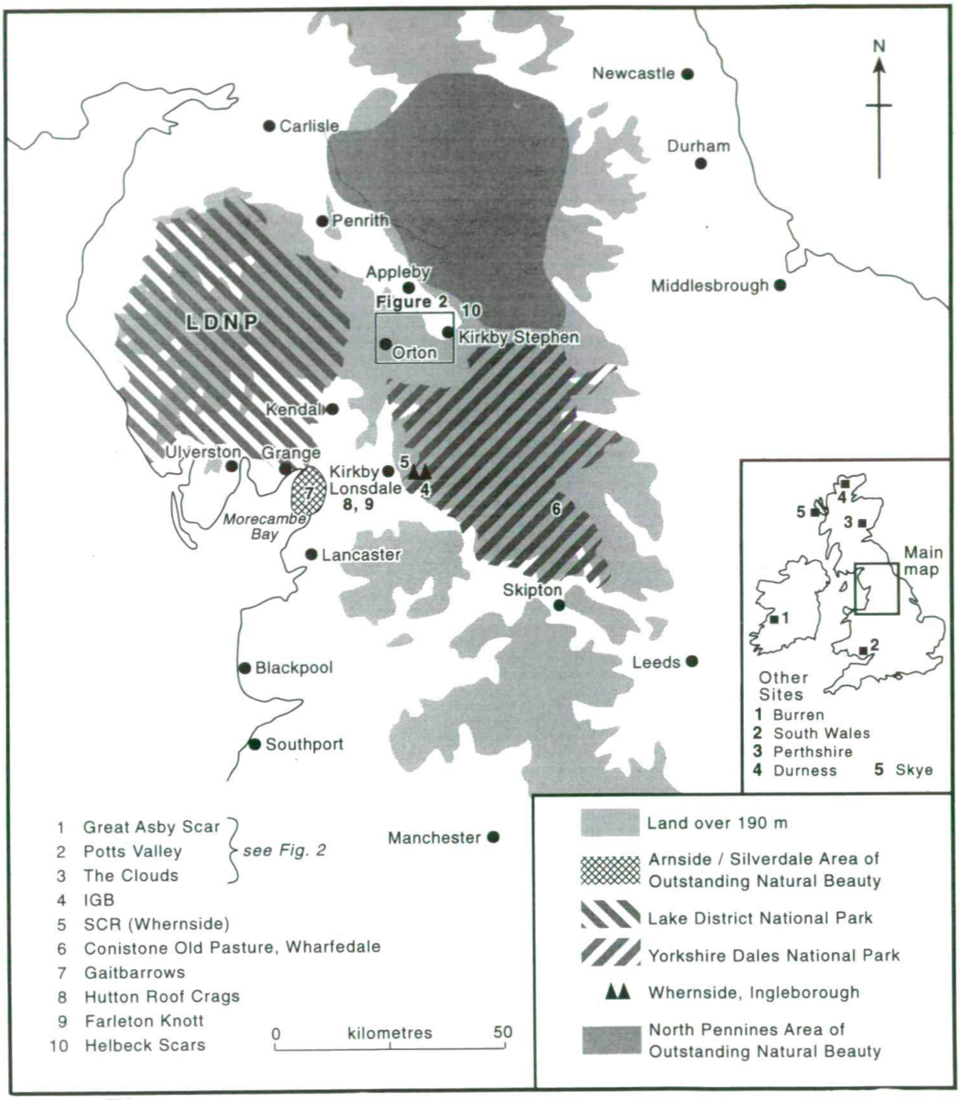

Figure 1 *Location map of Northern England*

All are developed in massive, pure mechanically-competent Carboniferous limestones. Great Asby Scar and Potts Valley lie on the Orton-Asby escarpment west of Kirkby Stephen, Cumbria, in Lower Carboniferous Asbian limestones (Figs. 2a & 2b). This is the most extensive area of limestone pavement outside the Ingleborough karst. The escarpment dips north-eastwards by a few degrees and undulates gently from west to east, thus causing a variety of dips. The pavements are best developed at Great Asby Scar where massive beds support scoured pavements. Potts Valley has less structural variety. The third north-western site, The Clouds, also has pavement on Asbian limestones extending into the lowest overlying Yoredale (Brigantian) limestones (Figs.3a & 3b). Structures here are influenced by the Dent Fault, a major fault line bounding the Askrigg Block in the west. Tectonism in the vicinity has caused strong folding and close jointing and The Clouds is essentially a pitching anticline with dips as high as 30 degrees.

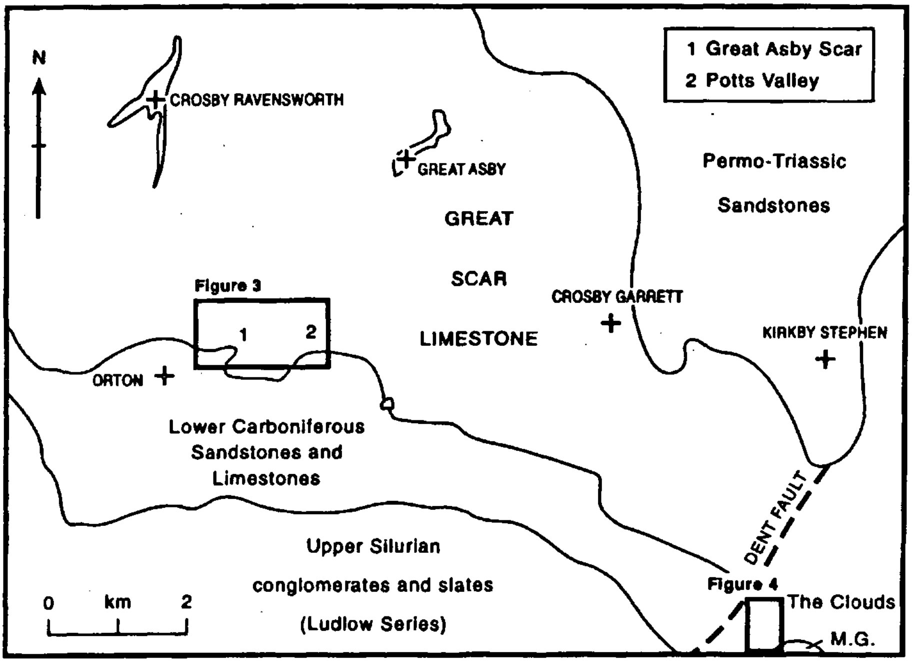

Figure 2a *Sketch map of geology of Orton - Kirkby Stephen area*

Both structural factors are highly significant for the limestone pavements. The three Yorkshire Dales sites are classic areas. The best examples in Britain of massive, scoured undissected pavement are on Ingleborough and Whernside (Fig. 1). They outcrop in massive, moderately well-jointed Asbian limestone. The pavements are dominated by the near-horizontal limestone bedding, with a regional dip of about 3-5 degrees to the north.

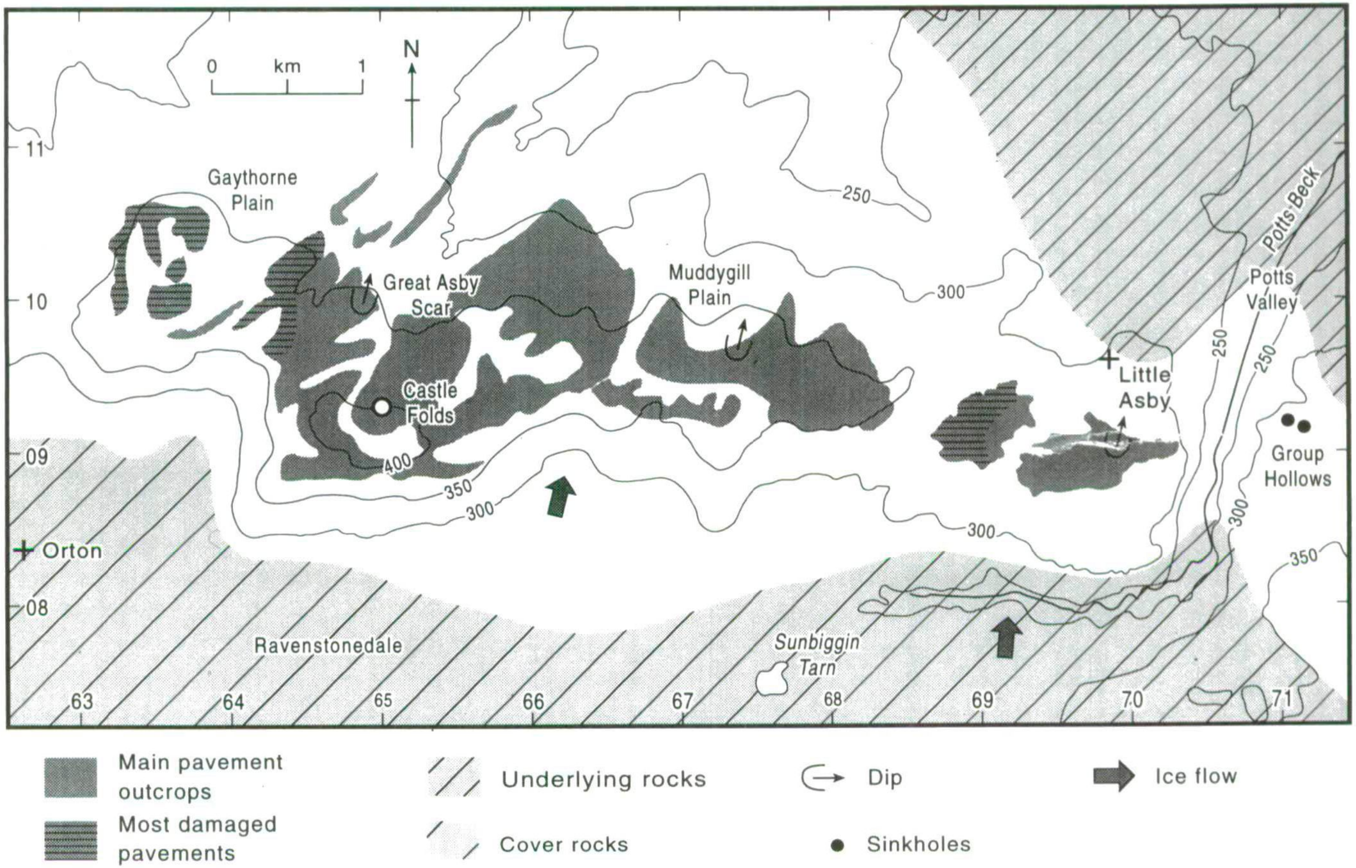

Figure 2.b *Limestone pavement outcrop of the Orton-Asby escarpment, Cumbria*

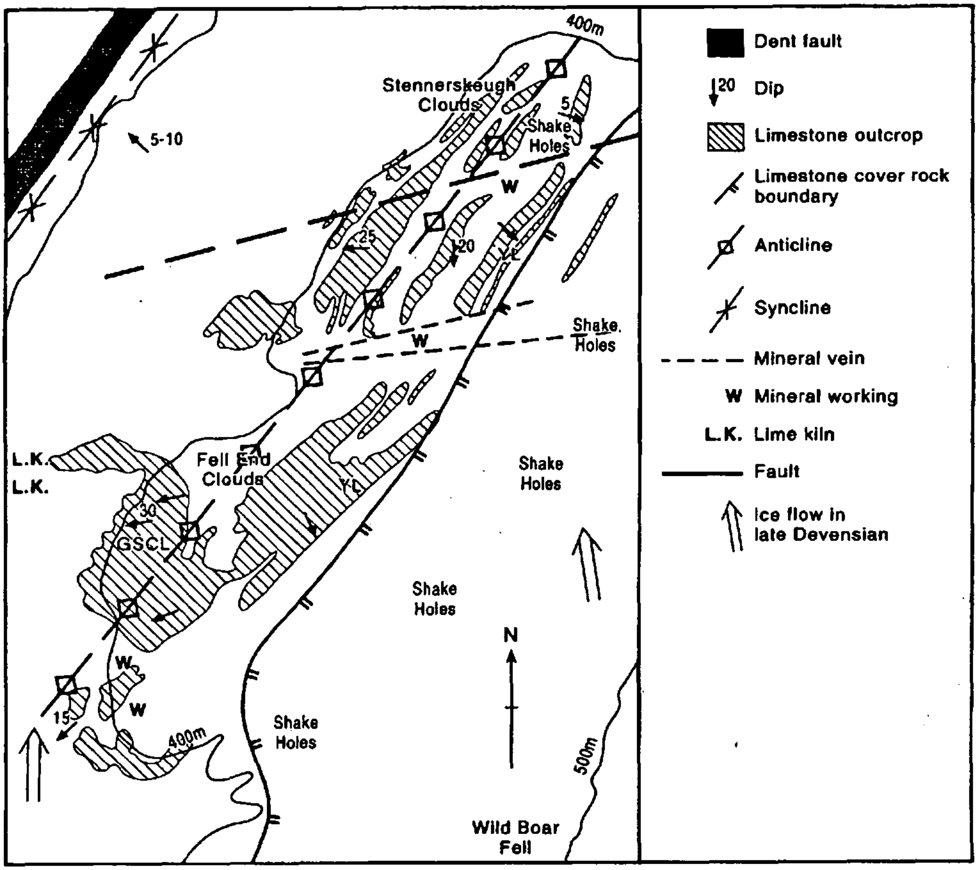

Figure 3a *Limestone pavements of The Clouds, Cumbria*

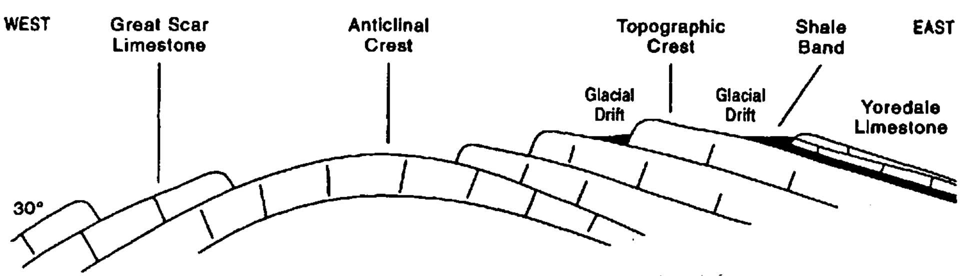

Figure 3b *Schematic cross section at Fell End Clouds (not to scale)*

On Ingleborough pavements occupy wide benches in the highest limestones at about 400 m, skirting the massif. Extensive pavements thus flank the north, south-east and south of the hill with narrower terraced sequences on the west side (*Fig. 4*).

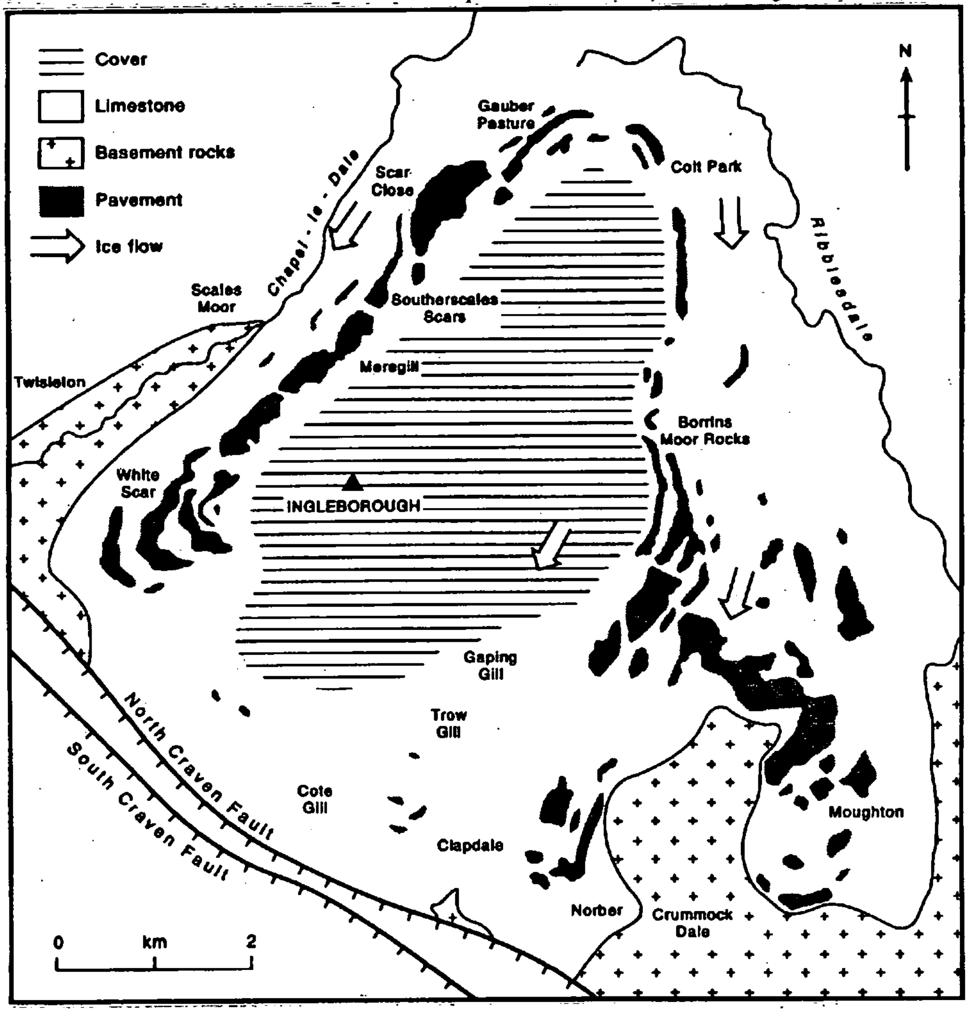

Figure 4 *Limestone pavement areas of Ingleborough, Yorkshire*

To the west, pavement is less extensive on Whernside, but there are still large areas of level pavement skirting the east, south-east and south flanks of this hill at the same altitude as on Ingleborough.

Two of the three sites near Morecambe Bay, Farleton Knott and Hutton Roof, are the two halves of a prominent 250 m hill in Holkerian and Asbian limestones. This hill is a fault-bounded, anticlinally-folded inlier of limestone affected by tectonism which produced other small limestone hills on the southern fringe of the Lake District (*Fig. 5*), including Gaitbarrows.

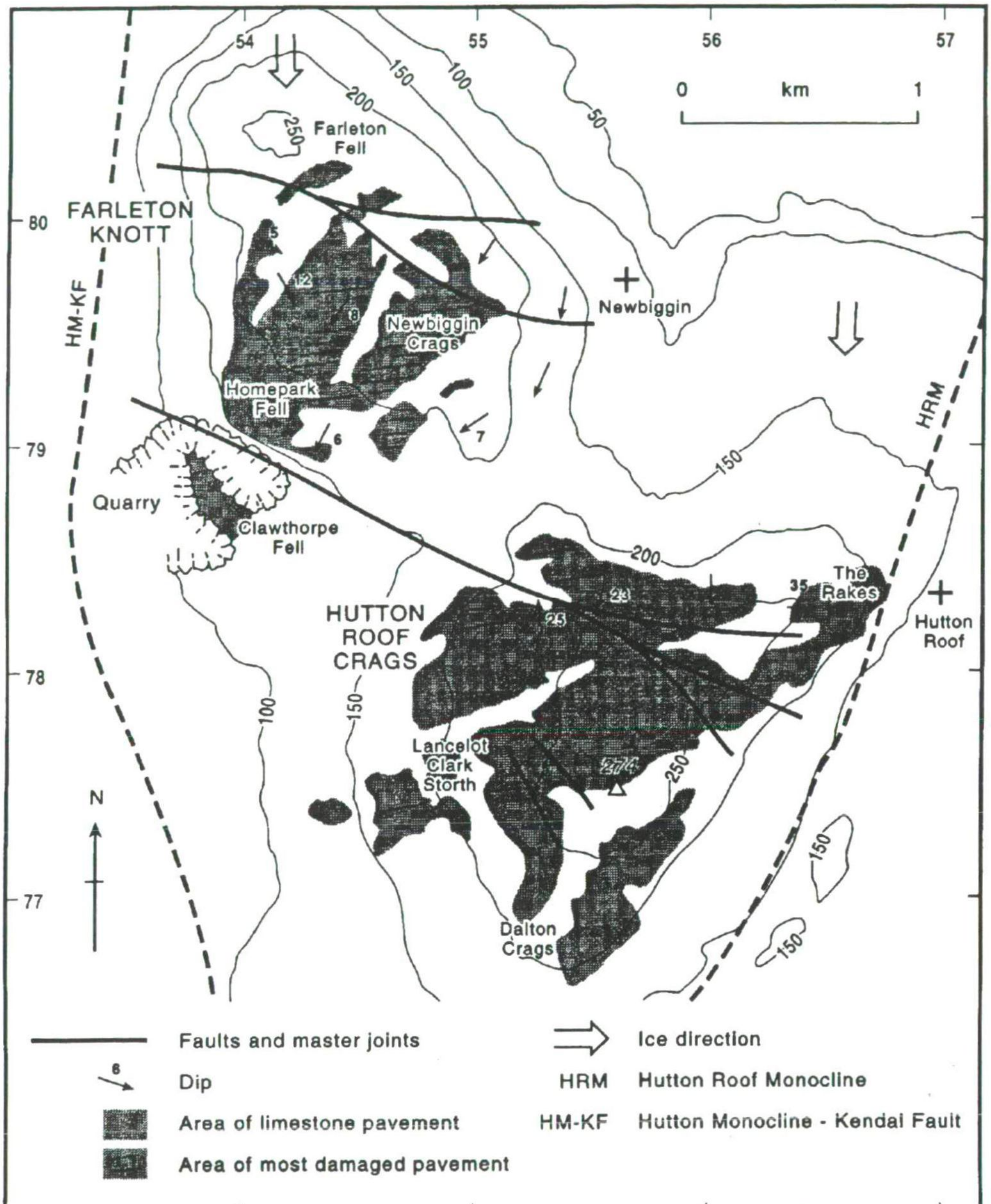

Figure 5 *The limestone pavement outcrops of Farleton Knott and Hutton Roof Crags, Cumbria*

Structures are varied with many minor undulations and faults breaking the outcrop into varied levels, dips and aspects. The most famous area is the steeply sloping Rakes on the east side of Hutton Roof. At Gaitbarrows (*Fig. 6*) the limestone dip gently southwards at about 3 degrees and the site is characterised by thickly-bedded limestones.

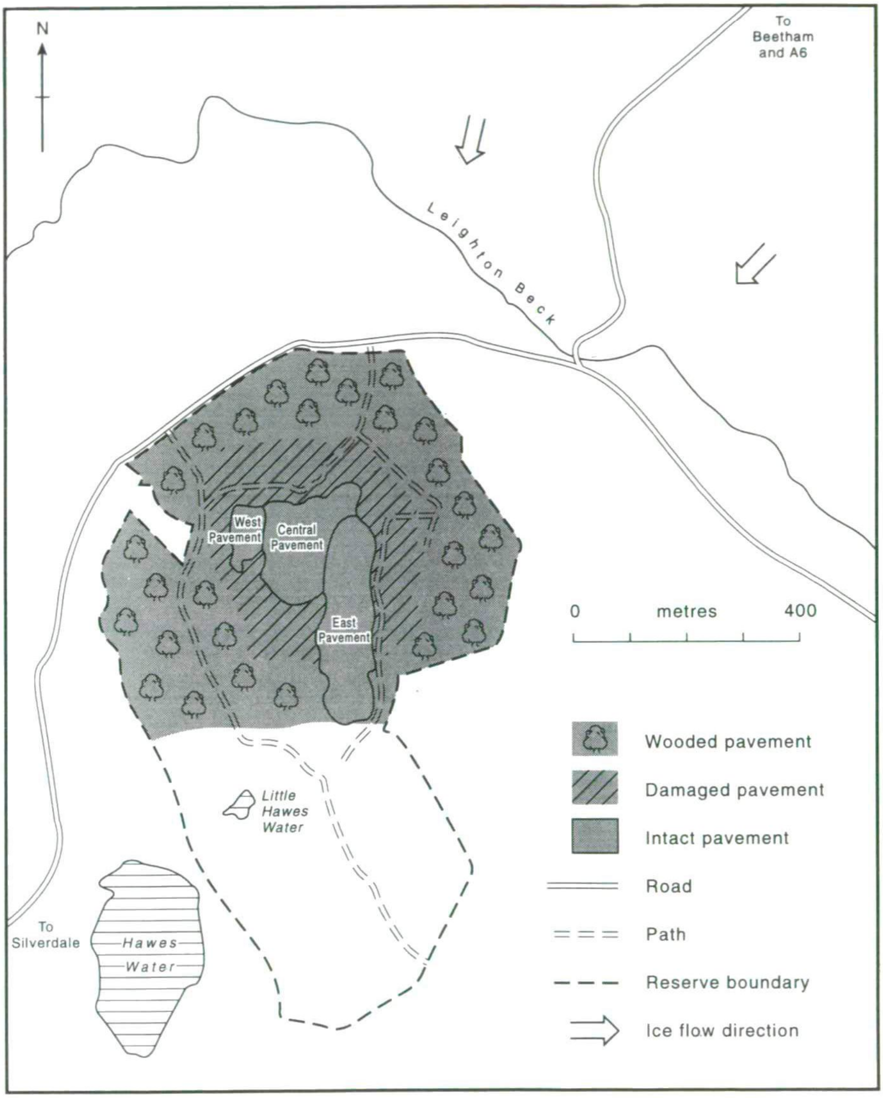

Figure 6 *Gaitbarrows National Nature Reserve limestone pavements, Lancashire*

This site is the lowest in altitude of all nine SSSIs, being below 50 m O.D. and is distinguished by excellent scoured undissected pavement with a varied fauna and flora. It has a mild wet oceanic climate contrasting with Farleton Knott nearby at 250 m, and even more so with the exposed cool, damp upland sites of the Yorkshire Dales and Kirkby Stephen areas.

DETAILED SITE DESCRIPTIONS

1: GREAT ASBY SCAR

Great Asby Scar National Nature Reserve contains varied intact limestone pavements and other broken limestone surfaces, separated by grass-covered areas with sheep-grazing (*Fig. 7*). Its most distinctive feature is that pavements cross a central synclinal valley. Small dry valleys and occasional surface drainage suggest former surface drainage in places although no water tracing is known. There are numerous small structural valleys and occasional small internal drainage depressions.

In the west badly damaged, well-laminated limestone has about 80% of its surface removed or displaced. Clints are small, mostly less than 1 m long, and runnels poor. Occasional gritstone erratics are found in grikes. Many clints are pedestal-shaped and well separated by damaged or grassy areas. Further east, excellent massive pavement dipping gently north-westwards from an anticlinal axis contains well-runnelled, well-dissected clints, deep grikes, and centripetal runnel networks.

These features occur in a massive bed overlying the main pavement (*Fig. 8*). Very smoothly scoured pavement, with simple networks of large, sharp-edged runnels, also occurs which is possibly at an earlier development stage than the rounded runnels, perhaps from deeper glacial scour down the dip slope. The sharp-edged runnels were probably formed by acid peaty waters. Remnants of the upper massive bed perched on sloping pedestals of underlying limestone about 10 cm in height suggest exposure about 2,000 yr ago (Sweeting 1966).

In the south-west very well-weathered pavement has highly fractured and laminated clints, although gaps suggest removal. However, mature development of thin, mossy vegetation on many of the lowered clints (rather than the rough gravelly surfaces typical of recently damaged surfaces) suggests that damage is old. Enclosure wall construction is the most likely reason for removal as the wall stone and neighbouring clints are similar. The wall dates from the Enclosure Period of nearly 200 years ago.

Greatest landform variety is found in the central synclinal valley, where pavements include massive, cushion-shaped clints underlain by pedestals of well-fractured limestone resulting in mushroom-shaped features. These develop along a sequence with pedestals becoming reduced, clint tops less runnelled and grikes narrower, until at the base of Castle Folds hill very smoothly-runnelled limestone disappears under cover. Towards the south-east outcrop is patchy and fractured with small clints because of lithology rather than human damage, although limestone has been removed for wall construction.

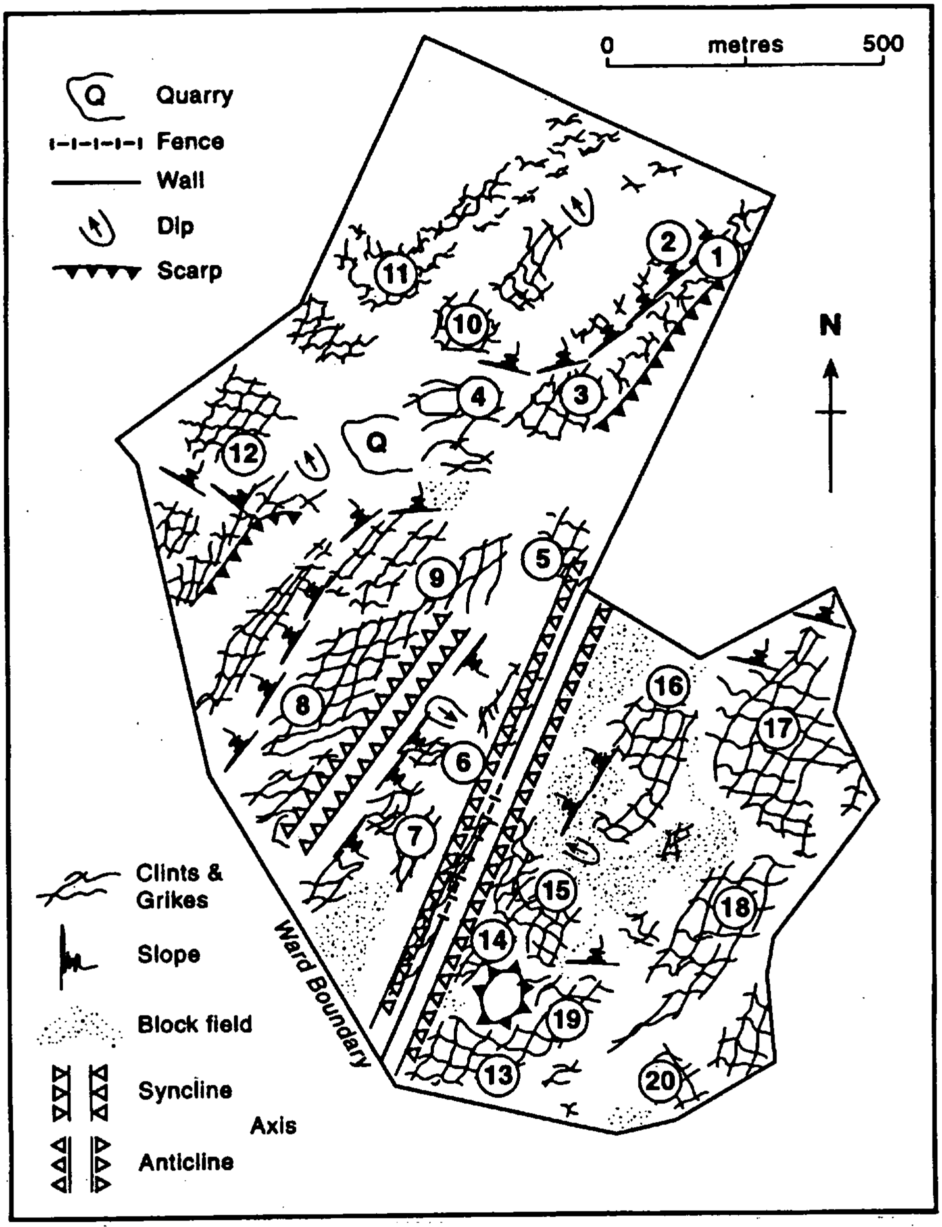

Figure 7 *Sketch map of the geomorphological features of Great Asby Scar National Nature Reserve*

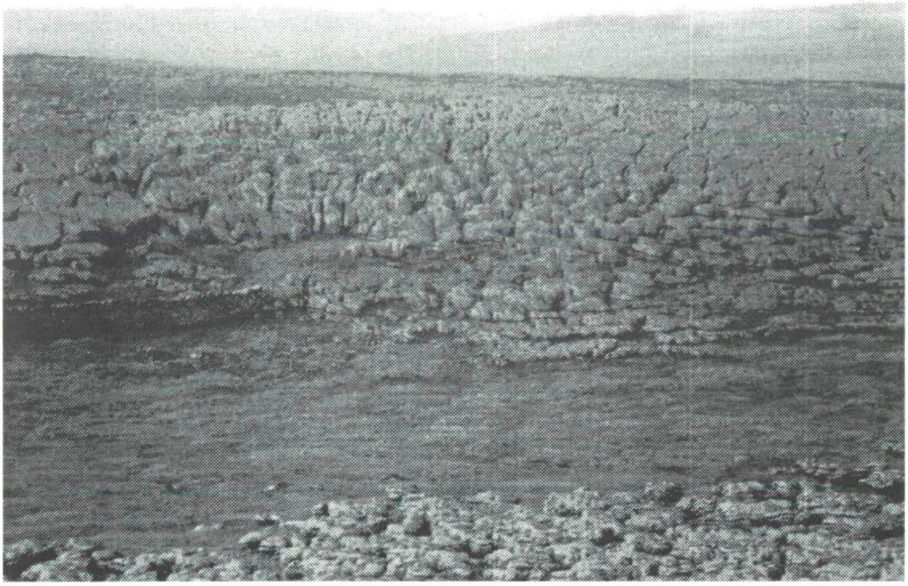

Figure 8 *Great Asby Scar National Nature Reserve, Cumbria: well-rounded massive clints on upper limestone bed near centre of syncline, flanked by more scoured limestone*

Pavement dipping at 12 to 16 degrees on the west of the syncline has striking features transitional between Rundkarren and Rinnenkarren. At its north end this outcrop has a massive moulded upper bed with centripetal Rundkarren around deep holes, some soil-filled. North and north-west of Castle Folds are the 'Shining Stones', extremely large, smooth-surfaced pavements possibly caused by locally stronger glacial scour. Lastly, pavement by the northern boundary includes very long and extremely well-runnelled clints.

Work published on Great Asby Scar describes the protection process there and discusses morphometry compared with other limestone pavements (Goldie, 1995, in press).

2: POTTS VALLEY

The site covers about 1.5 sq.km of patchy, very well-dissected pavement, limestone cliffs and screes, and grassland. The valley carries a very small misfit stream which is augmented by numerous small springs and maintains a surface course right across the limestone outcrop because of valley floor alluvium. Potts valley is discussed in material on the Howgill Fells and the Eden Valley region (Letzer, 1981; Underhill et al.,1988; and Mitchell, 1991, 1994).

The pavements are in limestones dipping northwards by as much as 10 degrees. They occur on both sides of the valley together with low scars of individual bed height. The pavements are less massive or continuous than many further west but clints are distinct, and many display good Rundkarren, although they are mostly separated by wide soil-filled grikes. Very narrow strips of pavement, just a few metres in width, run along some scar tops. A number of closed depressions and shakeholes occur around Group Hollows and there is no significant surface drainage.

Closed depressions and shakeholes here support the idea that the Potts Valley karst is more mature than limestone areas to the west. The unusually wide and soil-filled grikes can easily be accounted for because of the time available for their development if not scoured by Devensian ice.

3: THE CLOUDS

Pavements at The Clouds occur in several different limestones with examples of stepped pavement. Tectonism associated with the Dent Fault has caused strong folding (Underhill et al., 1988) which is reflected here in the landforms. Folded structures and narrow jointing provide an unusual geological environment for pavement development. Other nationally important limestone pavements have narrow jointing influenced by a major fault, but are not folded, for example south of Ingleborough; while other steeply dipping pavements, such as at Hutton Roof Crags, are neither so closely jointed nor so sharply folded. The general geomorphology of The Clouds is discussed by Goldie (1995, in press).

Limestone on the west of The Clouds mainly dips westwards, at angles up to about 30 degrees, while joint directions are diagonal to the hillslope and hillslope angles are similar to dips. In addition clints are small, usually below one metre long and 0.3 m wide. Since clint elongation is at an angle to the hillslope, runnels have a shorter distance downslope to develop on compared with Hutton Roof, for example. Updip angles lessen, following the anticline, to between 10 and 5 degrees on its crest. Massive limestones have larger clints, often more than 1 m long and 0.5 m wide. At Fell End Clouds the strike runs northwest-southeast as the anticline plunges southwards and the more massive limestones are both higher in altitude and lower in the sequence as they are followed north-eastwards. Well-laminated limestones in places produce a highly shattered surface more nearly Felsenmeer than pavement.

The pavements are stepped up the hillside (*Fig. 9*). Many clints in the north are large and diamond-shaped; further south they become small and knife-like. Deep narrow grikes separate the larger clints and surface solution features include Rundkarren and kamenitzas. The knife-edge clints tend to be separated by shallow grikes and display both lamellar and honeycomb weathering. Occasional sandstone erratics are wedged in grikes. Although mainly 5-9 degrees in places east of the anticline, the stepped pavements also dip steeply, up to 30 degrees, and dip direction varies from east to south-east. Near the top of Fell End Clouds striking embayments of nearly horizontal, massive limestone with scars about 2 to 3 m high on their inner edges have large, deep Rundkarren below the scars. Towards the outer edge clints become less well-runnelled and are merely well-fractured at the outermost edge. The inner edges are clear of significant drift and vegetation cover.

Figure 9 *The Clouds, Cumbria: extremely well-weathered north-facing pavements and scar edges at Fell End Clouds*

4: INGLEBOROUGH

The Ingleborough pavements, along with those on Whernside (Scales Moor), have been the focus of important karst research. Sweeting (1966) examined various aspects of their morphology and the processes acting on them and Williams (1966) compared them with limestone pavements elsewhere, especially in Western Ireland. Goldie (1976) discussed their morphometry and Waltham (1990) has published work on the karst of the area with relevance to the pavements. Although mostly nearly horizontal, these pavements are extremely varied, ranging from intensely fractured knife-edge clints at Clapdale Scars to great undissected sheets of scoured limestone at Scar Close (Fig. 4). In the west, Raven Scar has lamellar clints with well-developed grikes and, at the inner till edge of terraces, intensely well-runnelled surfaces, including centripetal networks. Faults interrupt the area, displacing scars and pavements slightly. The most southern area, White Scars, has varied, massive, moderately-sized clints. Clint shapes are highly irregular because of the well-developed runnelling. Flaggy and flaky weathered clints are smaller than the massive clints, with much natural loose debris. Occasionally Millstone Grit boulders are found.

Pavement at Souther Scales and Great Douk Cave Pasture has large clints and great morphological variety (*Fig. 10*). Transects of terraces here have well-runnelled clints near the inner, till boundaries. Central sections of transects have larger clints, often with single, very striking, large and sharp-edged runnels. The outer terrace edges are usually well dissected into smaller clints, possibly because of pressure-release effects or a longer period of exposure. Scar Close includes a range of grike features from very immature beginnings: very large rectangular clints (for example, 3 m by 7 m) with a central hump down their length, either side of which is edged by short Rundkarren; and very extensive undissected surfaces sustaining good vegetation on islands of till with peat (Gosden, 1968). The limestone is often well-veined with dendritic dissection related to drainage off such peat including that around the margins. There are also rectangular dissection patterns in the limestones. Aerial photographs show both clearly.

Figure 10 *Ingleborough, North Yorkshire: scoured limestone pavement on Souther Scales with large sharp-rimmed runnels*

Gauber Pasture is dominated by rectangular fractures, and moderately sized clints. Colt Park Wood, to the east, is well-vegetated pavement but extremely massive, with very deep grikes and large clints. Borrins Moor Rocks has extremely massive, rectangular well-runnelled clints. There are also features similar to Karrenfussnapfe.

Extensive pavements to the south of Ingleborough add to the variety, including the only steeply sloping pavements on Ingleborough, at Thwaite Scars. Norber has classic perched erratics and early studies of denudation rates used the erratics' pedestal heights (Goodchild 1890). Pavements in Crummackdale and Moughton are very well dissected, and there has been much disturbance for garden rockery stone. Clapdale Scars is a naturally well-fractured site near the Craven Fault with small clints predominantly of knife-edge linear type and fairly small grikes. There is much loose debris from natural causes, but also signs of clint removal. In Oxenber Wood massive, rectangular clints are incorporated in Iron Age settlement remains (Goldie 1976), consisting of in situ clints for hut foundations and transported stones used in the walls. Neighbouring clints are poorly runnelled though their surfaces are fairly smooth with solution depressions beginning. This may reflect the age of rock removal for hut building, probably about 2000 yr ago. Further, well fractured pavements are found in the between-fault zone, including Smearsett Scar and Feizor.

5: SCALES MOOR

Scales Moor has extensive bare limestone outcrops amongst acid grassland at about 400 m, without trees or shrubs and is littered with numerous gritstone erratic boulders. Prominent scars form at Twisleton Scar End, and the pavements here are slightly better vegetated partly from being sheltered below the main plateau level. Scales Moor is heavily grazed by sheep, thus confining tree and shrub vegetation to the grikes. At Twisleton Scar End the land is enclosed and grazing more controlled than on the open moor and this may permit better vegetation. The sequence here of limestone scars, screes and benches with narrow bands of pavement is one of the best examples nationally of stepped limestone pavement or Schichttreppenkarst. The scars are between 2 m and 15 m in height, reflecting bed thickness.

Research at Scales Moor includes studies of soil and vegetation cover, the gritstone erratics, and solution processes, especially on the peaty waters (Sweeting 1966, Williams 1966). About 50 cm of solution can have occurred in the last 12,000 years, although local variations around this average will contribute to the variety of features.

Pavements all over Scales Moor show fine Rundkarren and kamenitzas. Limestone dip and clint size influence the variety of runnels, their lengths, depths and network complexity varying with available clint length downslope. Scales Moor is particularly distinctive for excellent examples of centripetally-arranged runnel networks on horizontal limestone surfaces. Such networks are also found on the Ingleborough pavements. Runnels radiate around a central hole. They may be caused by biologically-influenced solution beneath the leaves of trees which once occupied the central holes. Similar patterns, although less well developed, are found around present-day trees, for example, on Newbiggin Crags, in Wharfedale and at Scar Close. Their existence on bare pavement suggests formerly greater vegetation.

6: CONISTONE OLD PASTURE

Pavements outcrop on the east side of Wharfedale in Great Scar Limestone (George et al., 1976). As they are on the eastern edge of these easterly-dipping beds they are overlain up the valley side by Yoredale Limestones and Millstone Grit Series. Their morphology, lithology and human impact have been compared with other sites (Goldie 1976, 1990). Archaeological literature on the area describes evidence of the nature and length of influence of human activities on the pavements (Raistrick and Chapman, 1929).

Conistone Old Pasture includes several pavements edged by small scars and separated by grassy, soil-filled areas. These pavements have well-runnelled, thickly-bedded clints, although small (*Fig. 11*). The runnels are predominantly Rundkarren, but kamenitzas also occur with small-scale rippling and pitting solution features. In the north, pavement is virtually horizontal despite the regional dip. Further south, some outcrops incline 10 to 15 degrees and slope has obviously influenced runnel orientations and network development. Clints here are also larger, thus giving more scope for runnel development.

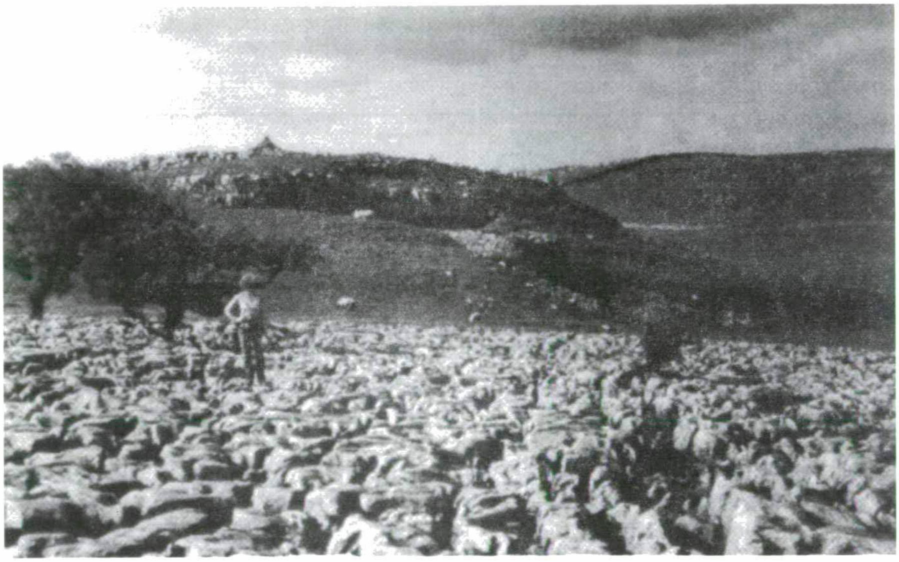

Figure 11 *Conistone Old Pasture, North Yorkshire: well-runnelled and well-dissected limestone pavement with limekiln in background*

The narrow valley limits outcrop extent in Wharfedale, and near Conistone the limestone terraces are half the width of those at Ingleborough. Higher pavement outcrops are limited by drift and soil cover, and the best pavement-forming limestones disappear beneath cover rocks. This area has the best pavements in Wharfedale, although there are numerous other outcrops. Conistone's pavements are particularly attractive and interesting, partly for their location near dry fluvial lan‹ ›rms.

7: GAITBARROWS

Gaitbarrows National Nature Reserve is only 0.5 km in diameter, but incorporates a large range of important landforms. About half is well-wooded, while much of the open pavement has shrubs and trees. Distinctive sub-areas include the massive central exposure at the north end with individual limestone beds as thick as 3 m. Landforms include kamenitzas of varying development stages; immature but deep grikes which frequently do not intersect; pedestals of protected limestone beneath; and massive, well-veined, scoured pavement. Clints can be several metres long. There are also grike clusters and Rillenkarren on some clint edges. This area contains numerous erratics of gritstone wedged in the grikes. There is considerable variety of well-dissected pavement elsewhere at Gaitbarrows, especially around the central massive site, some with good rectilinear grike patterns. These clints are large, a few metres in length, although often narrow if one major joint set is dominant. Some pavements have an undulating general surface because of glacial moulding. In the south there are smaller clints, 1 m in length or less, with many loose limestone blocks from natural processes. In addition there are artificially stripped areas with numerous interesting features, although few mature karst forms, and messy areas where damage has left loose, tilted or overturned clints. Other pavements are well covered with ground vegetation plants, and their morphology is difficult to see except on close examination, which reveals well dissected clints with Rundkarren.

Gaitbarrows has been the focus of considerable research interest since 1980. Earlier published work was largely botanical, for example, Wheldon and Wilson (1907) and Ratcliffe (1977). This site was top of the Ward and Evans national floristic survey (1976). Frankland (1980), Goldie (1986) and Rose and Vincent (1986a, 1986b, 1986c) have considered various aspects of its geomorphology. Rose and Vincent (1986a) studied the central-area kamenitzas and associated them with calcite veins, an idea relevant to understanding more dissected pavement elsewhere. There are also numerous immature grike features, different from the kamenitzas. They are invariably occupied by plants and often aligned along veins: many have developed into elongated slits or are joined by very narrow cracks along veins. They are clearly the early stages of grike development and in any one small area a variety of such stages can be observed. The veins are clearly important though it is hard to explain exactly why (Rose and Vincent, 1986a). Possibly grikes on more maturely-dissected limestone pavements have developed like this, although a problem in evaluating the hypothesis is that solution removes the vein.

8: HUTTON ROOF CRAGS

The most well-known part of Hutton Roof Crags (Fig. 5) is The Rakes, a classic example of a sloping pavement (Williams, 1966; Sweeting, 1966; Waltham, 1974). However, this is not the only important feature at Hutton Roof Crags; there are many small tracts above and west of The Rakes of well-dissected pavement at varying dip angles, mostly 5-10 degrees. These areas display varied surface solution features including kamenitzas, Rundkarren and Rinnenkarren. They are moderately well-vegetated, disguising the nature of this area as a disrupted Schichttreppenkarst. The westernmost outcrops at Lancelot Clark Storth are bare, well-preserved, dipping pavements with undulations thought to be formed by glacial scouring. Upslope eastwards are more broken outcrops and further south are the wooded pavements of Dalton Crags.

The Rakes consist of three major bedding plane-guided outcrops, mainly dipping at angles of 25 degrees and above. They are dissected by two major orthogonal joint sets, oblique to both dip and strike. They were scoured by northerly ice and hence almost certainly along the direction of strike. Because of the relationship between joint set angle, dip and hillslope, there are diamond-shaped clints sideways on to the steepest slope (*Fig. 12*). Thus different lengths of outcrop downslope are runnelled by Rinnenkarren of varying length. These Rinnenkarren are the finest such runnels in England, Wales or Eire, and being lightly vegetated are thus a very striking landscape feature. There is virtually no damage from garden rockery stone extraction. A fourth stratum of limestone lying beneath the three massive beds is without pavement outcrops for lithological reasons and forms a Felsenmeer of lamellar debris.

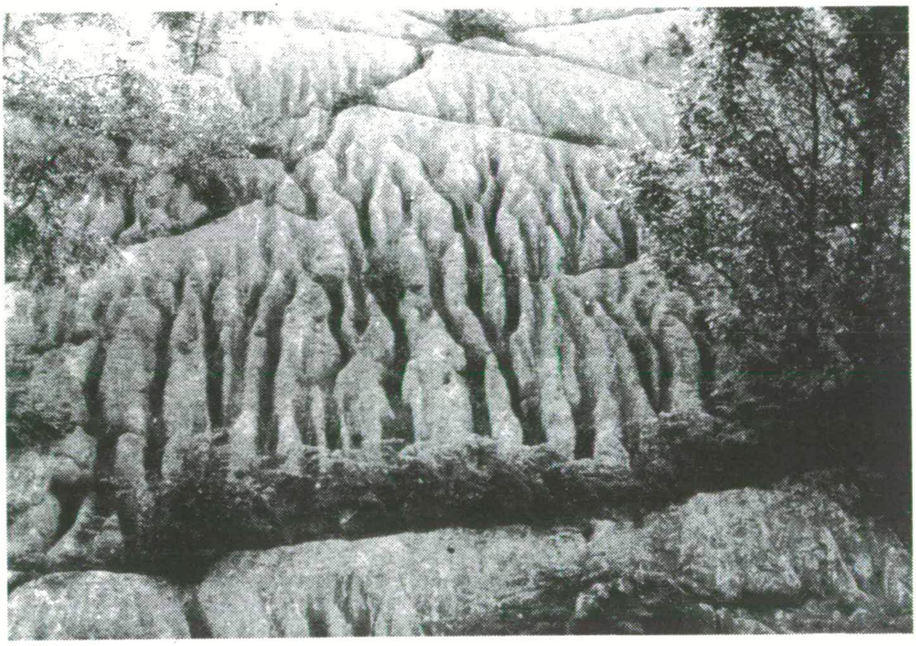

Figure 12 *Hutton Roof Crags, Cumbria: well-runnelled diamond-shaped clints at The Rakes.*

Glacially transported limestone boulders are scattered throughout the site, perched on pavement surfaces, or lying beneath woodland vegetation. Small scoured scars, several metres high, are also common because of the fracturing and folding, and are most prominent on the west-facing sides of the strike valleys at The Rakes.

Hutton Roof still has much soil and vegetation, but this has retreated, revealing Rundkarren at pavement margins. The exact time-scale of development of such cover, and its subsequent retreat or removal, has been difficult to determine, partly through the lack of dateable sediments (Pfeiffer 1989). Much change must be attributable to human occupation.

9: FARLETON KNOTT

Farleton Knott (Fig. 5) has many minor structural features and thus a great variety of limestone pavements in massive, fossiliferous limestones, including pseudobreccias. An important influence on morphology has been glacial scour from the north, but drift cover is thin. There is no known surface drainage on Farleton Knott, and no known caves, though water must pass through the massif as there are springs emerging around the hill.

The area is easily divided into three sub-areas by geological structure and relationship to glacial scour. The most northerly part is Farleton Fell, which includes quite steeply inclined pavements dipping south. Nearby is nearly horizontal pavement, well-developed with rectangular clints and numerous transported limestone boulders standing on protected pedestals (*Fig. 13*). The steeper pavements are at angles between about 14 and 20 degrees, with small to moderately-sized clints (Goldie, 1981). Solution features on these slopes include kamenitzas and solutional ripple marks, akin to Trittkarren. Because of the relationship between grike directions and topographic slope, features are not comparable to The Rakes, but more chaotic, reminiscent of Hohlkarren. To the west, however, this outcrop swings slightly northwards, clints are larger and the surface is more like The Rakes, although at about 12 degrees, and the pseudobrecciated limestone is roughly honeycombed.

The second sub-area, Holme Park Fell, contains gentler pavements dipping south-westwards at 3 to 8 degrees. Because of their location down-dip from the highest point over which the ice flowed, they have been strongly ice-scoured. Holme Park Fell contains the site's largest and smoothest pavements and prominent smooth-based large Rundkarren with sharp upper edges characteristic of peaty water solution. Down-dip clint edges are closely runnelled by smooth Rundkarren characteristic of receded soil and vegetation (*Fig. 14*). This area is also very striking for being littered with transported limestone boulders as at Farleton Fell.

Figure 13 *Farleton Fell, Cumbria: glacially-transported limestone boulders on sloping limestone pavement.*

Figure 14 *Holme Park Fell, Cumbria: well- ıelled limestone pavement with Holme park Quarry in background.*

Newbiggin Crags is the third sub-area and is important for its beautiful, horizontal and near-horizontal pavements displaying nationally outstanding networks of Rundkarren. It possesses very striking edge scars, several metres high with striking vertical solution grooves and fallen blocks. There are two main well-runnelled pavement surfaces in these massive beds, one containing large rectangular clints. Complex runnel networks here are probably influenced by solution under trees. The second bed has smaller clints with a very slight south-westward dip with the most striking examples of Rundkarren networks, nearly all focusing southwards downdip along the clints' longer dimension. Between Newbiggin Crags and Farleton Fell extensive outcrops of pseudobrecciated limestones have limited runnelling.

The great variety of runnelling on Farleton Knott reflects the variety of slopes, aspects, lithologies, depth of glacial scour, and soil and vegetation cover both past and present. Nowhere on Farleton Knott is as steeply sloping as The Rakes at Hutton Roof. The sloping pavements have probably remained free of soil and vegetation since de-glaciation (Vincent & Lee, 1982).

Corbel (1957) thought that the hills around Morecambe Bay, including Farleton Knott, represented a relict Tertiary tropical karst, but others (Gale 1980, Vincent and Lee 1981) have disputed this. The present consensus emphasizes structural influence on hill shape. Structures in this area are discussed by Adams et al. 1990).

DISCUSSION

1. The influence of glaciation

Limestone pavements are stripped bedding-plane features and in Britain are almost always the result of glacial scour in their basic form, while their solution features are the result of varying conditions in which solution can take place (Williams 1966). The sites discussed here experienced glaciation in the most recent, Devensian, glaciation, in different ways. Some may even have been sheltered from it by their closeness to basal ice sheds, particularly Potts Valley and The Clouds.

Although near these ice sheds, Great Asby Scar probably had extensive scour by ice flowing northwards over the escarpment's highest point from the local ice centre on the Howgill Fells, and guided by the limestone bedding. Some slackening or variation of scour intensity, however, would be possible here and this may explain some of the more massive Rundkarren on beds higher than the general pavement level. The higher bed of massive limestone found in central parts may have escaped removal as ice scour slackened over a local anticlinal rise (Fig. 8). The runnels on these limestones are so large that some component of their morphology may be the result of survival of pre-Devensian solution forms. Alternatively meltwater or enhanced biological activity related to former vegetation cover might have caused accelerated corrosion.

An early settlement at Castle Folds, and other archaeological remains, is evidence favouring the idea of a greater vegetation cover in the recent past.

Pollen evidence from Sunbiggin Tarn, south of the escarpment, provides further support (Webster, 1969).

Potts Valley was initially formed when Potts Beck had a much larger catchment, before capture of its headwaters by the River Lune (King, 1976). Thus it is pre-glacial and was excavated to close to its present depth in pre-glacial times although modified during the glacial periods of the later Pleistocene. This modification was slight as the valley is located near a basal ice shed (Mitchell, 1994). This protection from deep glacial scour may be the cause of very maturely-dissected limestone pavements here which appear to be of considerable, and unusual, age. Many of the landforms, or some elements of them, may thus pre-date the Devensian glaciation, although dates are lacking.

Location near the local ice source of Wild Boar Fell, to the south-east, has been an important influence on the morphology of The Clouds' pavements. The depth of scour from this nearby and small ice source may not have been great. Basal ice sheds were located in this area at various stages of the Pleistocene (Mitchell 1994). If parts of the pavements at The Clouds escaped severe glacial scour, because of their aspect, this would help to explain some local characteristics, in particular the extremely mature Rundkarren below small scars near the top of Fell End Clouds. Here outcrop edges are not scoured clear to form smooth scars as in other glaciated karsts of northern England, but have a bevelled graded change from the lower to the upper bed through a highly weathered sequence of runnelling (Fig. 9). This occurs on north-facing scars which would be in the lee of ice flowing off Wild Boar Fell. Higher outcrops aligned north-south have scoured edges. The well-runnelled scars may retain some elements of pre-Devensian erosion.

Glacial scour is clearly the most important geomorphological process forming the Ingleborough and Scales Moor pavements. The glacier flowed down Chapel-le-Dale from the north and although small it had a relatively steep gradient and so was probably powerful erosively (Waltham 1990). It achieved clean scour of the limestone beds, producing proto-pavements and the excellent scoured limestone scars. Sweeting (1966) stressed that the most striking pavements occurred where intensive glacial scour affected the most massively-bedded limestones. In higher parts of the plateau above Conistone, depressions between the pavement slabs are thought to have been produced by ice-margin meltwater erosion. Drainage channels may have formed rapidly during the retreat of the Devensian glacier in Wharfedale and fossilised as climatic amelioration allowed drainage to return underground.

Gaitbarrows' landforms are thought to be the consequences of the intense glacial action characteristic of heavily-burdened glaciers at their seaward end. Thus they complement higher altitude pavements, such as at Farleton Knott and Ingleborough. Because of low altitude Gaitbarrows is also among the few pavement sites likely to have been influenced by sea-level changes in the Pleistocene (Frankland, 1980). It is not likely, however, that marine planation has significantly influenced present forms. If Gaitbarrows, at about 35 to 40 m O.D., ever experienced such processes it is likely that it was very early and that Devensian scour would have had much greater effects on present-day features than any such marine planation.

Some elements of pavement form, such as deeper grikes, may have a pre-glacial component (Williams 1966). Pigott (1965), in his model of glacial scour, and Goldie (1981), in her extension of the Pigott model, also both thought this a possibility. Observations at Gaitbarrows yielded evidence that deeper grikes have an inherited element (Rose & Vincent 1986c). Glacial erratics stuck in grikes suggest that the grikes must have been open when the erratics were dropped. The Morecambe Bay pavements appear to have been scoured more deeply, or for longer, than the higher pavements at Holme Park Fell further east. Comparisons of grike morphometry at Holme Park Fell with sites near Morecambe Bay (Rose and Vincent 1986c) indicated that Holme Park Fell has a mixture of grike widths suggesting inheritance here of some components of the grikes from before glaciation. Morphometric data for the whole of Farleton Knott (Goldie, 1981) suggest that Holme Park Fell was probably the most scoured part of this particular hill. It was estimated by Rose and Vincent (1986c) that about 72 mm of grike opening has taken place at Holme Park Fell since the last glaciation.

Glacial scour of Hutton Roof Crags has been extremely important for both erosion and deposition. Apart from the scoured pavements, numerous small scars are clearly glacially scoured, with smooth rounded scars showing limited runnelling, contrasting with The Clouds. Because of its prominence above surrounding lowland, Farleton Knott would have received the full impact of southerly-flowing ice from the Lake District and north. The ice action has scoured and plucked the limestones, guided partly by bedding planes, has transported large limestone boulders short distances and then deposited them on the scoured limestone pavements. There is a particularly striking distribution of these boulders on the limestone beds which swing round and down the north-west flank of Farleton Fell. Many now stand on limestone pedestals sheltered from solution by the boulders. It is thought unlikely for any features in this area to predate the Devensian glaciation because of its prominent exposure to the full force of ice from the north.

2. Geological influences

Lithological and structural factors are two extremely important influences on limestone pavement distribution and characteristics (Williams 1966, Sweeting & Sweeting 1969, Goldie 1976). Faults, bedding planes, joints and other smaller fractures influence both macro- and micro-topography. Very closely-jointed limestones produce highly shattered surfaces often with thin, easily broken clint tops, the debris from which fills the grikes. They contrast with the better pavements found in the massive, thickly-bedded rocks. This is well exemplified at several of the sites, especially The Clouds.

Altough there is massive limestone, the pavements at The Clouds are generally very well dissected, with relatively small clints, because of high joint density resulting from closeness to the Dent Fault tectonic zone. Small clints limit the development of complex runnel networks, although at the Clouds the clints are well runnelled by Rundkarren so far as their extent permits. Structural influence has also produced a variety of low scars and benches. Clapdale Scars on Ingleborough is another example of close jointing influenced by proximity to a tectonic zone, in this case the Craven Faults.

Structural influences have also clearly affected geomorphic variety at Farleton Knott, Hutton Roof Crags and Conistone Old Pasture. Fracture patterns at Farleton Fell (Fig. 15) have been established by Moseley (1972), who identified the expected rectangular joint pattern, and often a third set of joints between. Many pavements show this rectangular pattern, but Newbiggin Crags is a particularly good example, also showing the effects of the third joint direction with triangular-shaped clints, or runnel patterns markedly influenced by this third alignment. On a larger scale, several major and minor faults run across the whole site and are responsible for topographic breaks, particularly on Farleton Fell and the upper part of Hutton Roof Crags. These structures have also produced low scars, small structural depressions and dry valleys.

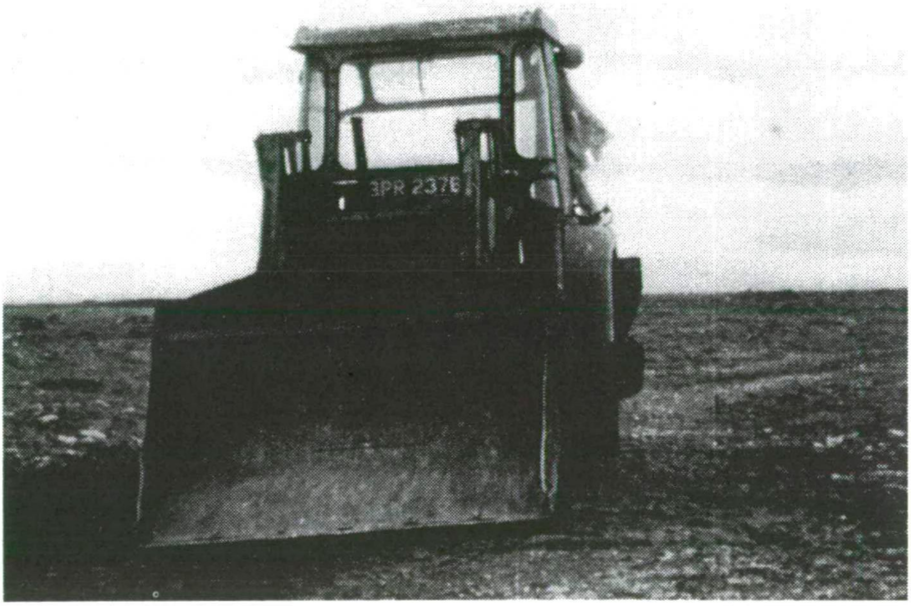

Figure 15 *Gaythorne Plain, near Great Asby Scar, Cumbria: badly-damaged limestone pavement with extraction machinery on site*

Other sites need comment. At Great Asby Scar and Potts Valley, bedding differences are very important with numerous features resulting from the juxtaposition of very different limestones. Lithological studies have examined the effects of sparry calcite content in limestones on limestone pavements (Sweeting & Sweeting 1969, Goldie 1976), but further examination of lithological properties in relation to pavement characteristics is needed. The possible influence of calcite veins in the limestones on the evolution of pavement forms has already been considered for Gaitbarrows.

3. Morphometric analysis

The Table and graphs (*Figs. 16 & 17*) summarize morphometric data for many of the pavement areas mentioned. Comparative morphometric work on limestone pavements in N.W. England shows the clints at Great Asby Scar extending over a greater size range than other Cumbrian pavements with some significantly larger clints, e.g. Shining Stones (Goldie, 1995). Overall the Cumbrian pavements are similar morphometrically to Ingleborough's, but there are some long clints in the Cumbria sample, mostly from Great Asby Scar. The Hutton Roof pavements measured were those above The Rakes on gently inclined beds. They are more dissected than elsewhere on Farleton Knott, and in Yorkshire (Goldie 1981). Hutton Roof Crags had the smallest clints sampled, averaging 2.3 m by 0.9 m, and quite deep grikes (average 1.17 m). This may reflect proximity to the Hutton Roof Monocline which may have increased stresses, and therefore joint densities, in the limestones.

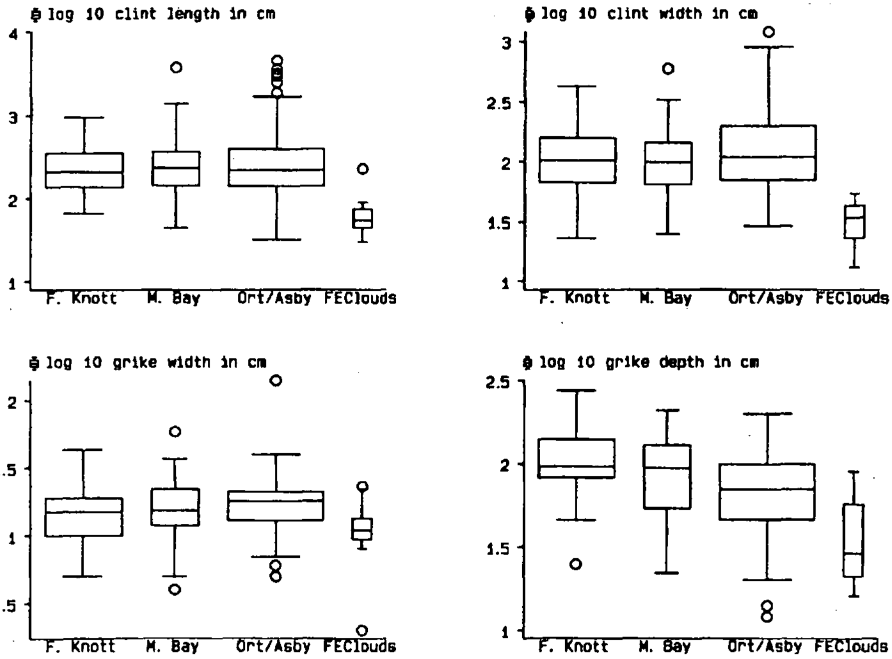

Figure 16 *Box plots comparing clint and grike data for Orton-Asby with three other Cumbria areas*

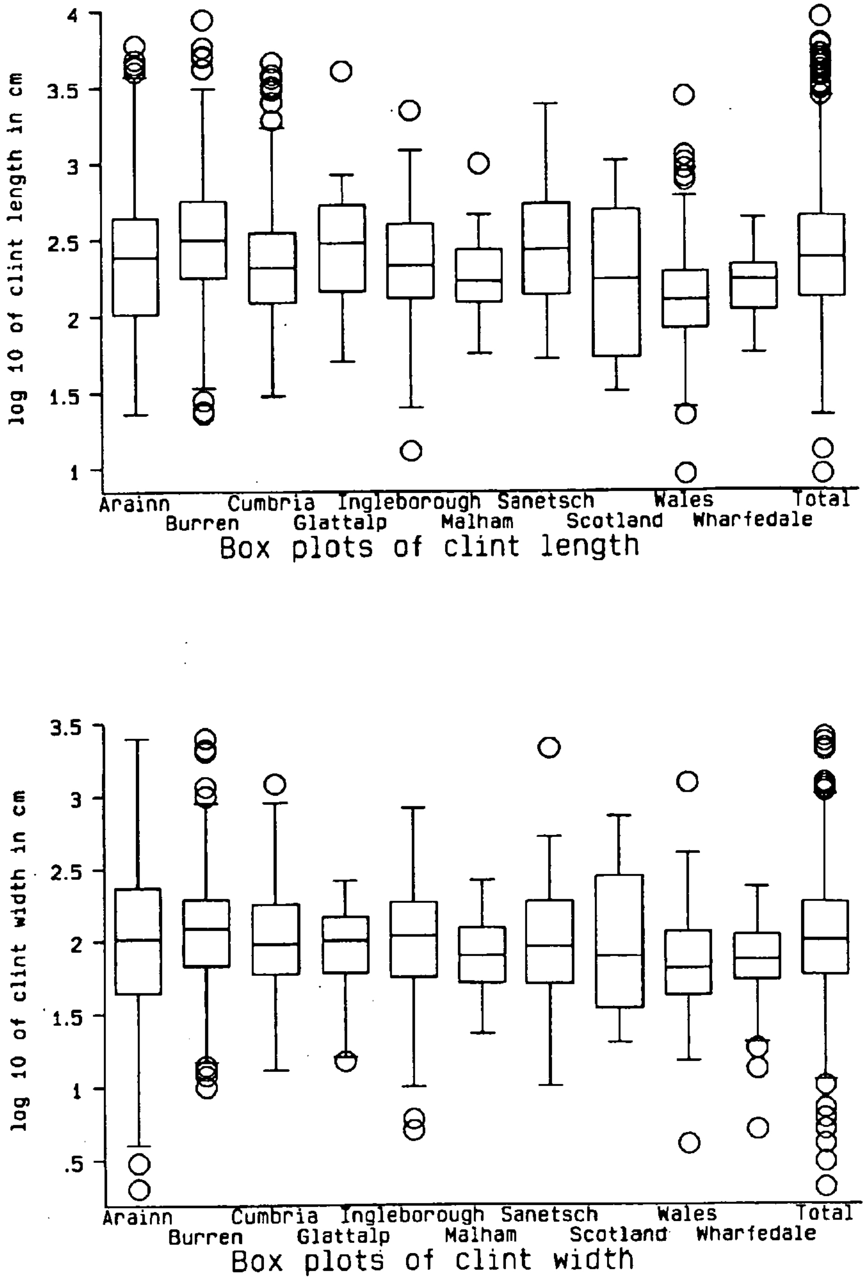

Figure 17 *Box plots comparing clint data for all sample areas*

The Farleton Fell pavements are quite well-dissected, more so than at Holme Park and Newbiggin Crags, with deep grikes (average depth 1.21 m) and clints averaging 2.75 m long and 1.05 m wide. Clint length also varied more at Farleton Fell than at Newbiggin Crags, which has squarer clints. Possibly this difference results from the effects of the faulting (Fig. 5) in the Farleton Fell area. Holme Park Fell had the least dissected forms as already discussed.

4. Human influence

There has been considerable discussion of human impact on limestone pavements (Goldie 1976, 1981, 1986, 1987, 1990, 1993). The influence on the Orton-Asby escarpment and at Gaitbarrows has been the most extensive and profound of the limestone sites discussed here. Surfaces west of Great Asby Scar especially have suffered from modern activities. Limestone has been used in the past from the Orton-Asby escarpment for agricultural lime, as evidenced by limekilns, but the most important modern activity has been clint removal for garden rockery stone, with extensive and direct impact on the exposed limestone. Great Asby Scar National Nature Reserve was set up in 1976 to protect the remaining pavements from this damage. Although the Reserve contains the best remaining examples of limestone pavement on the escarpment, it also includes damaged pavements within the Reserve. Damage has produced the Felsenmeer at Gaythorne Plain.

Scree and Felsenmeer at The Clouds mostly reflect lithological influence rather than human interference, although lead mining has disturbed the limestone locally. Because the limestone is well jointed and also well dissected, the outcrop margins are broken down by natural processes. Exploitation for rockery stone appears to be slight. Mineral working (Dunham and Rose 1985) affects mostly Fell End Clouds. Lead mining practice has left its mark on the landscape in the form of surface diggings, shattered debris and the artificial valleys produced by local hydraulic mining. There is also a walled area cleared of limestone pavement for pasture improvement on the west side of The Clouds.

Ingleborough and Scales Moor have experienced direct human impact. The most recent extensive activity was in the 1960s and included mechanised removal of clints. There is evidence of earlier removal for lime-burning, sheep folds and other structures such as walls (Goldie, 1976), as there is for other sites such as Great Asby Scar. Parts of Twisleton Scars were very extensively worked in the modern period, with stone removed from the northern end. Known areas of clint removal on Scales Moor became well vegetated with moorland grasses within ten years. The Conistone area has evidence of fairly old damage for wall and rockery stone removal and archaeological evidence suggests pressure on the limestone outcrop for construction since the earliest settlement of the area (Raistrick & Chapman 1929). Oxenber Wood near Ingleborough shows direct evidence of such early impact (Goldie, 1976).

Around the intact pavements of Gaitbarrows are large areas of freshly-stripped pavement-type surfaces resulting from clint removal for the garden rockery trade. The bedding planes so exposed eventually develop new features and not all are covered by evolving soil and vegetation. Shallow depressions, some scalloping and sharp Rillenkarren can be found developing on those stripped surfaces which have remained bare. About 40 to 50% of the original exposed pavement at Gaitbarrows was affected by this limestone removal. In addition, it disturbed better-dissected but still intact pavements, especially displacing clints round the edges of limestone outcrops. The Nature Reserve was set up here in 1977 to protect the area from further damage.

On Hutton Roof human activities have had most distinct effects on the landforms in the west, especially at Lancelot Clark Storth, where the pavement morphology has been markedly altered. Old limekilns in the locality would have used pavement. There are also small public quarries to the north. The morphology of the outcrop was most affected here by more recent removal of limestone for garden rockeries up to the mid-1970s. Results vary from the occasional lack of top, solution-runnelled clints to extensive areas systematically stripped of these features leaving rough bedding planes (Ward and Evans, 1976; Goldie, 1976). Newbiggin Crags also has obvious recent artificially-stripped clint surfaces with much sugary debris lying around, left from this removal. Immature runnel development here may be related to long-continued clint-top removal.

Landforms on Farleton Knott have also been extensively affected by human activities. Removal of limestone is documented from before the Second World War. After the war access was improved and removal became more mechanised. In 1969 for example, 2,423 tons of limestone was taken from this site (English Nature files). Large areas of Newbiggin Crags, the central pavements, and the southwestern end of the site around Holme Park Fell have displaced clints, rough bedding plane surfaces and rubbly debris, all signs of clint removal. In addition, deep quarrying southwest of Holme Park Fell has removed a previously existing dry valley and accompanying pavement features. Also parts of Clawthorpe Fell southwest of the quarry, at Curwen Woods, have completely gone and the remains of Clawthorpe Fell stand isolated now, surrounded by the quarry. East of Newbiggin Crags attempts have been made to aid the grassing over of the stripped limestone surfaces and only isolated small outcrops of clints now remain.

5.Protection

Limestone pavements in Britain have come to need protection as a result of centuries of damage caused by the removal of their top surfaces, the clint-tops. This removal occurred for a number of reasons, for example, for lime-making, and walling. However, clint removal for garden rockery stone, intermittently from at least the late nineteenth century, became a very serious threat for the landscapes in which pavements occur, from the 1960s onwards. The scale of activity escalated because of mechanisation, and large areas of limestone pavement were being devastated by the removal of the clint-tops, which have the attractive solution runnelling which makes the pavements so interesting. Clint removal also damaged the flora in the grikes and because much of this

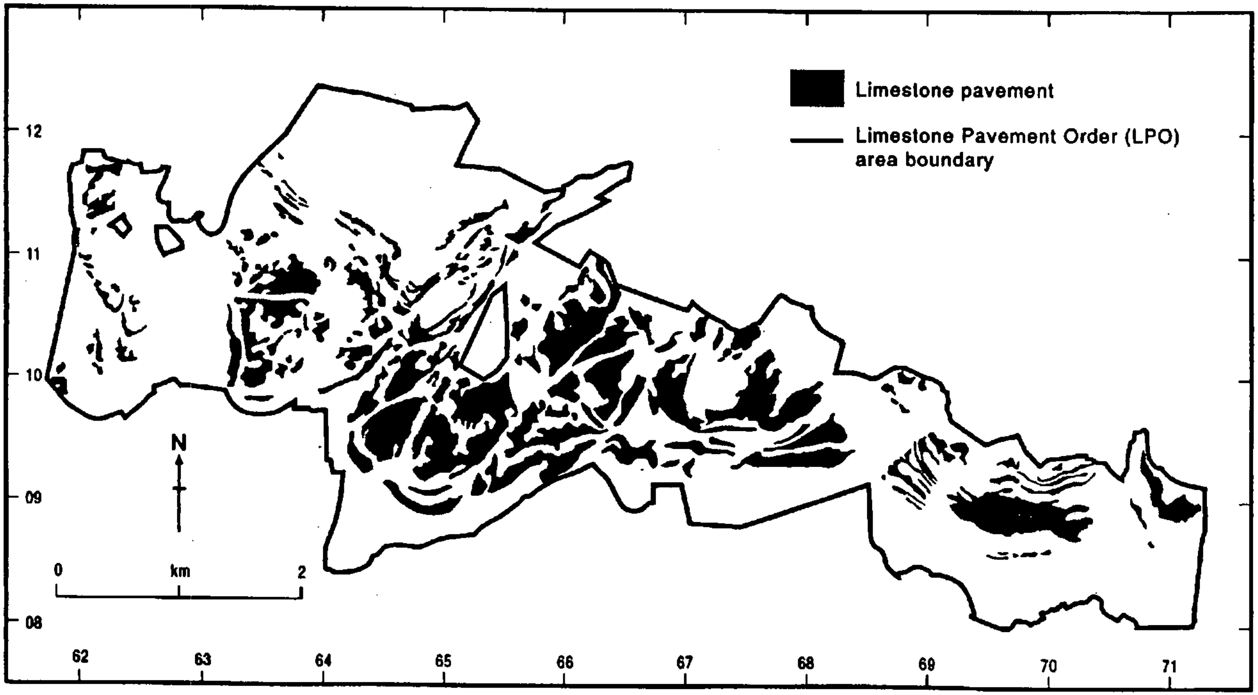

Figure 18 *Orton-Asby Limestone Pavement Order (LPO) area, Cumbria*

flora is unusual steps began to be taken in the 1960s to prevent further damage. Designation of a site as a Site of Special Scientific Interest, as in the case of the sites discussed here, did not in itself prevent damage occurring. Several sites were purchased by either private or public bodies, and made into Nature Reserves. Such Reserves provide very strong protection but other pavement areas, although in areas such as National Parks, were weakly protected by planning controls.Continuing damage meant that various bodies and individuals, such as the Nature Conservancy Council (now English Nature), supported parliamentary legislation to prevent these irreplaceable landforms from being damaged further. This legislation (1981) is described in detail by Goldie (1993). The most important device is the Limestone Pavement Order (LPO) which is made on an area of limestone pavement. Various activities on that site are then prohibited and transgressions are legal offences punishable with fines. In area where LPOs have been made, experience so far suggests that they have been effective both in preventing damage and in raising public awareness of the issue. All of the sites discussed here are covered by LPOs, and Ingleborough, Gaitbarrows and Great Asby Scar are also National Nature Reserves (run by English Nature). It is interesting to note that public awareness is a very important protection in itself. The pavements that are well-visited by tourists, such as those in the Yorkshire Dales National Park, have tended to be less prone to any casual damage, even in the period before LPOs were put in force, than those in the more remote, less-visited areas.

CONCLUSION

The characteristics of the pavement sites which have merited inclusion in the Geological Conservation Review are highly varied. There are many other good outcrops of limestone pavement in various parts of Northern England, and many outcrops of these features in other parts of Britain, which have been excluded. Not all sites can be included: those which have been incorporate the best and most extensive outcrops and represent the variety of this beautiful but vulnerable landform, which brings so much to the surface attraction of the areas in which it is found.

REFERENCES

Adams, A.E., Horbury, A.D., & Abdel Aziz, A.A. 1990 Controls on Dinantian sedimentation in south Cumbria and surrounding areas of north-west England. Proc. Geol. Assoc. 101,1, 19-30.

Corbel, J. 1957 Les Karsts du Nord-ouest de L'Europe. Inst. Etudes Rhodaniennes Mem. et Doc. 12, Lyon.

Dunham, K.C. & Wilson, A.A. 1985 Geology of the Northern Pennine Orefield, Vol. 2, Stainmore to Craven. Brit. Geol. Surv. Economic Memoir, NERC, HMSO, London.

Frankland, H. 1980 Field Notes. Institute of British Geographers field visit to Gaitbarrows. English Nature files, Blackwell.

Gale, S.J. 1980 The geomorphology of the Morecambe Bay karst and its implications for landscape chronology. Z.f. Geomorph. N.F. 25,4, 457-469.
Gale, S.J. 1984 Quaternary hydrological development in the Morecambe Bay karst, north-west England. Norsk geogr. Tidsskr. 38, 185-192.
George, T.N., Johnson, G.A.L., Mitchell, M., Prentice, J.E., Ramsbottom, W.H.C., Sevastopulo, G.D. and Wilson, R.B. 1976 A correlation of Dinantian rocks in the British Isles. Geological Society of London, Special Report No.7.
Goldie, H.S. 1981 Morphometry of the limestone pavements of Farleton Knott, (Cumbria, England). Trans. Cave Res. Assoc. 8,4, 207-224.
Goldie, H.S. 1986 Human influence on landforms: the case of limestone pavements. Ch. 27 in: New Directions in Karst. (Eds. K. Paterson and M.M. Sweeting), Norwich, Geobooks, pp.515-540.
Goldie, H.S. 1987 Human impact on limestone pavements in the British Isles. In: Kunaver, J. (ed.) Karst and Man. Proceedings, International Symposium on Human Influence in Karst, Postojna, Yugoslavia. Dept. of Geography, University E.Kardelj, Ljubljana, 179-199.
Goldie, H.S. 1990 Limestone Pavements in Wharfedale and Littondale, North Yorkshire. Durham Geographical Fieldwork, vol.1. Dept. of Geography, University of Durham.
Goldie, H.S. 1993 The legal protection of limestone pavements in Great Britain. Environmental Geology 21, 160-166.
Goldie, H.S. 1994 The Geomorphology of Great Asby Scar, Cumbria. 15pp. Unpublished field guide, IGCP 299 Conference: Changing Karst Environments, Oxford and Huddersfield, 1994.
Goldie, H.S. 1995 The limestone pavements of Great Asby Scar, Cumbria, U.K. Environmental Geology (In Press).
Goodchild, J.G. 1890 Notes on some observed rates of weathering of limestones. Geol.Mag. 17, 463-466.
Gosden, M.S. 1968 Peat Deposits of Scar Close, Ingleborough, Yorkshire. J. Ecology 56, 1, 345-353.
King, C.A.M. 1976 Northern England. Methuen, London.213pp.
Letzer, J.M. 1981 The Upper Eden Valley. In: Field Guide to Eastern Cumbria. Quaternary Research Association, London, ed. J. Boardman, 43-60.
Mitchell, W.A. (ed.) 1991 Western Pennines Field Guide. Quaternary Research Association, London.
Mitchell, W.A. 1994 Drumlins in ice sheet reconstructions, with reference to the western Pennines, northern England. Sedimentary Geology 91, 313-331.
Moseley, F. 1972 A tectonic history of northwest England. J. geol. soc. Lond., 128, 561-598.
Pfeffer, P. 1991 Geookologische Einheiten eines Limestone Pavement Gebietes, Hutton Roof Complex (SSSI), Cumbria, Nordwest England. Diplomarbeit des Geographischen Instituts der Universitat Tubingen.
Pigott, C.D. 1965 The structure of limestone surfaces in Derbyshire. Geog. Journ. 131,4, 41-44.
Raistrick, A. & Chapman, S.E. 1929 Lynchet Groups of Upper Wharfedale, Yorkshire. Antiquity 3, 165-181.
Ratcliffe, D.A. 1977 A Nature Conservation Review. Cambridge University Press. 401 pp.

Rose, L. & Vincent, P.J. 1986a The kamenitzas of Gait Barrows National Nature Reserve, north Lancashire, England. Ch.25 in: New Directions in Karst. (Eds. K.Paterson & M.M. Sweeting), Norwich, Geobooks, pp.473-496.

Rose, L. & Vincent, P.J. 1986b Alkalinity measurements in karst water studies. Ch.1 in: New Directions in Karst. (Eds. K. Paterson & M.M.Sweeting), Norwich, Geobooks, pp.1-15.

Rose, L. & Vincent, P.J. 1986c Some aspects of the morphometry of grikes. Ch.26 in: New Directions in Karst. (Eds. K. Paterson & M.M. Sweeting), Norwich, Geobooks, pp.497-514.

Sweeting, G.S. & Sweeting, M.M. 1969 Some aspects of the Carboniferous limestone in relation to its landforms. Mediterranee 7, 201-209.

Sweeting, M.M. 1966 The weathering of limestones. In (Ed.Dury, G.H.) Essays in Geomorphology. Heinemann, London, 177-210.

Underhill, J.R., Gayer, R.A., Woodcock, N.H., Donnelly, R., Jolley, E.J., & Stimpson, I.G. 1988 The Dent Fault System, northern England- reinterpreted as a major oblique-slip fault zone. Journal of the Geological Society, London, 145, 303-316.

Vincent, P.J. 1981 Some observations on the so-called relict karst of the Morecambe Bay Region, North-West England. Revue de Geologie Dynamique et de Geographie Physique 23, 2, 143-150.

Vincent, P.J. & M.P. Lee 1981 Some observations on the loess around Morecambe Bay, North-West England. Proceedings of the Yorkshire Geological Society 43,3, 281-294.

Vincent, P.J. & M.P. Lee 1982 Snow patches on Farleton Fell, southeast Cumbria. Geog. J. 148, 337-342.

Waltham, A.C. (ed.) 1974 Limestones and Caves of North-West England. David & Charles, Newton Abbot. 477 pp.

Waltham, A.C. 1990 Geomorphic Evolution of the Ingleborough karst. Cave Science 17,1, 9-18.

Ward, S.D. & Evans, D.F. 1974 Limestone Pavements: A botanical survey and conservation assessment based on botanical criteria. Institute for Terrestrial Ecology (NERC), Bangor, Wales.

Webster, R. 1969 The Romano-British Settlements of Westmorland, a study in cultural ecology. Unpublished Ph.D. Thesis, University of Reading.

Wheldon, J.A. & Wilson, A. 1907 The Flora of West Lancashire. Henry Young, Liverpool.

Williams, P.W. 1966 Limestone Pavements: with special reference to Western Ireland. Transactions of the Institute of British Geographers, 40, 155-172.

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ON THE DEVELOPMENT OF THE CLASSICAL DINARIC KARST IN SLOVENIA

Peter HABIC

ABSTRACT

Geotectonic, geomorpho-hydrologic and climatical position between the Mediterranean and the Alps in the Southern Europe is decisive for the classical Dinaric karst. In the geographic situation between the 45.30° and the 46.30° of the northern latitude and 13.30° and 16° meridian of the eastern longitude the karst developed from the sea level (even below it) to the highest peak in the Julian Alps (*Triglav*, 2864 m). Prevailing part of this karst is built in Cretaceous and Jurassic limestones and dolomites, through partly in Triassic and older as well as in younger Palaeogene and Neogene carbonate rocks.

Recent researches called attention to the traces of Pre-quaternary arid and humidic, warm and cool period transformations (P. Habic, 1992). The differentiated neotectonics decidingly influenced the formation of the Dinaric karst relief as particular units of folded and overthrusted structures either uplifted or subsided and were exposed to variously intensive karst transformation. Development phases are evidenced in the karst relief forms and in the remains of various deposits on the karst surface and in the underground. In fossil caves, fluvial sands f.i. are preserved from the highest areas to the sea shore.

INTRODUCTION

In Slovenia the Dinaric karst is situated among the Adriatic and Pannonian basin and the eastern part of southern Limestone Alps. The karst surface is composed by inherited and recent forms which resulted in geomorphological development in several phases. The traces of old fluvial and fluviokarstic planation are preserved since the period when the carbonate rocks were limited and impounded from all the parts by the impermeable rocks. After general planation of stirred up post-orogene geologic base, the period of erosional or solutional deepening and dissection followed. Particular areas were either uplifted or subsided by consecutive tectonic movements, uncovered and opened limestones and dolomites were exposed to karstification.

There are shapes and sediments preserved in relief which should originate in different climatic conditions. Differentiated exposure of variously resistant rocks against erosion and solution was connected to climate too. In cooler Quaternary periods the surface on impermeable rocks lowered more quickly than in karstified carbonate rocks. The last ones were in general less resistant in warm and humid climatic conditions.

The main relief forms developed within the treated area somewhere from Mio-Pliocene onwards. Karst in southern Slovenia comprises nine thousands of square kilometers only, but morphologically extremely heterogeneous surface developed.

THE REVIEW OF IMPORTANT GEOMORPHOLOGICAL TREATISES

In general quite a lot was written about the Dinaric karst. The first synthetical review was done by J. CVIJIC (1893, 1918, 1960). His treatises are essential as numerous younger researchers followed his examples (D. FORD & P. WILLIAMS, 1989; Ph. RENAULT, 1992. The CVIJIC's scheme of cyclic development of karst surfaces known. After him J. ROGLIC became famous (1957, 1960, 1965) by his original views to deep circulation, rim corrosional widening, fluviokarstic and corrosional karstic transformation.

The former fluvial origin of Dinaric karst surface in Slovenia was sustainingly defended by A. MELIK (1935, 1961, 1963). According to him the karstification did not start earlier than the epirogenetic uplifting of miocenic levelled surface. Thus in cold Pleistocene periods the fluvial processes strengthened, on karst poljes in particular and the waters accumulated mechanical scree there which filled the underground channels too and caused the inundations.

Interesting data about the intensiveness of recent solute processes in Slovenia were gathered by I. GAMS (1965, 1985), the same author wrote the monograph on recent karstological results (1974). He studied the effects of accelerated corrosion, poljes and blind valleys genesis and other forms of contact fluviokarst.

General concept of geomorphological karst development in Slovenia was presented by D. RADINJA (1972). The impact of climate on relief formation in Slovenia tried to define M. SIFRER (1990). He emphasized the difference between Pliocene and Pleistocene periglacial and glacial formation of the relief. Structurally and tectonically controlled forms in Dinaric karst were subject of P. HABIC researches (1968, 1990).

Among the important treatises on speleogenesis let us mention the work of S. BRODAR (1952) and R. GOSPODARIC (1976, 1986), who deepened the speleogenetical knowledge by chronostratigraphy of cave sediments.

THE DISTRIBUTION OF KARST IN SLOVENIA

Some 9000 sq. km or 44% of the territory of Republic Slovenia can be classified as karst area. Over two thirds of this territory (6300 sq. km) consist of limestone, mainly Mesozoic, whereas karst areas on other rocks (dolomite, conglomerate, calcarenite and breccia) occupy some 30% of the entire karst areas of Slovenia.

The karst in Slovenia is commonly divided into three major units: a) **the Alpine karst**, b) **the Dinaric karst** and c) **the isolated karst of the intermediate area** (sub-Alpine karst and sub-Dinaric karst).

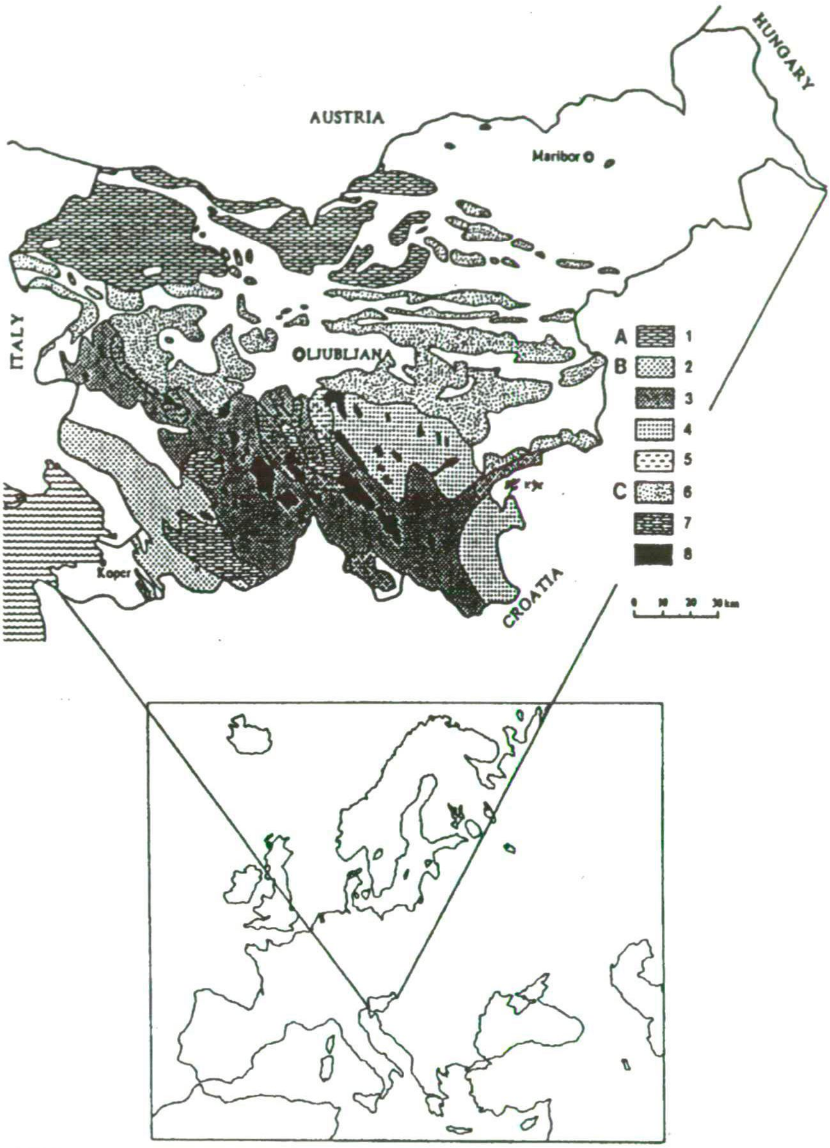
a) **The Alpine karst** (the *Julian Alps*, The *Karawanke*, the *Kamnik* and *Savinja Alps*) can be classified, using M. HERAK's (1977) tectogenetic criteria, as the fractured orogenetic karst. The Palaeozoic carbonate rocks remain preserved only in form of lenses and are the basis of the karst in the Karawanke Mountains.

The Alpine karst region is dissected by deep valleys, lying between ridges of an altitude from 1000 to 2800 m. The plateau-like segments below the highest peaks are small, but quite extensive in *Komna, Pokljuka, Jelovica, Mezakla* etc. in the border part of the Alps.

In high levels of Alpine karst one can find all karst forms known in the Northern and Southern Limestone Alps (big dolines - *kontas*, snow dolines with vertical walls - *kotlic* (sing.), all kind of karren etc. Recently the 11 km long alpine cave Poloska jama and some potholes with depth between 700 and 1200 m (*Crnelsko brezno* 1198 m, *Skalarjevo brezno* 911 m, *Brezno pri gamsovi glavici* 817 m, *Poloska jama* 704 m) have been discovered. In other Alpine karst areas the karstic hydrology is often the only karst phenomenon. The underground waters can rise to the impervious ground but flow out to normal valleys. The karst waters come out in the sources in the Quaternary deposits at the bottom of the valleys or directly from the steep rocky slopes in waterfalls (the *Savica*, the *Boka*, the *Soca* etc.) The Alpine karst waters are comparatively pure because the surface is barren, without thicker layers of soil and less populated.

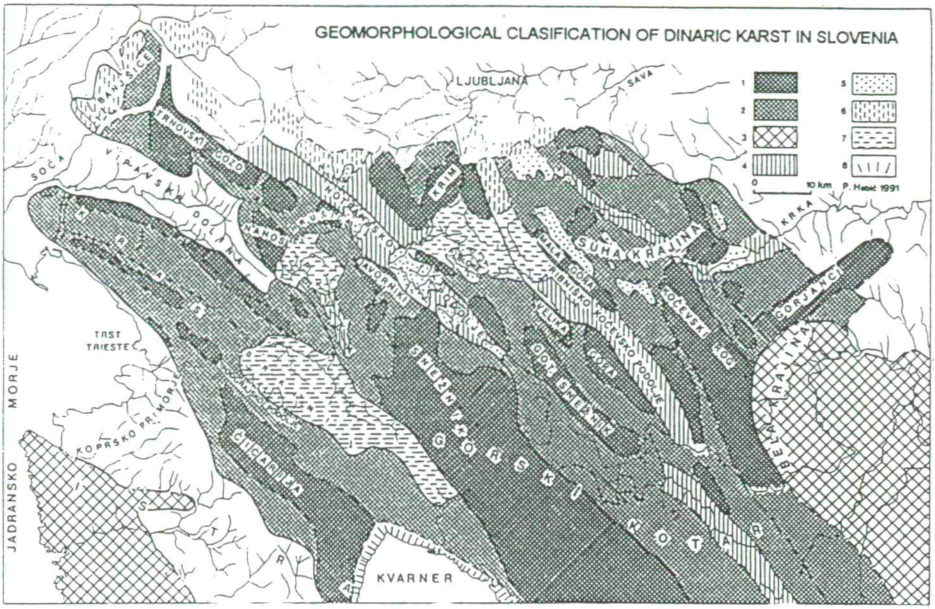
b) **The Dinaric karst** includes continuous karst areas in western and southern Slovenia. This is the orogenetic accumulation karst (M. HERAK, 1977) consisting mainly of Mesozoic and Palaeogene, tectonically fractured limestones and dolomites that are often overthrusted and thus attain, secondarily, great thickness. The impervious rock basis is lying deep under the surface, but really important are the lithological and structural differences, in particular the inserted layers of less permeable dolomites and of the Eocene flysch which constitute, in places, the basis or are inserted between karstified rocks and thus hinder or direct the outflow of water along the tectonical units. In this deep karst almost all phenomena that are characteristic of the out-flow, through-flow or impounded contact karst are to be found.

The Dinaric karst can be divided into three enlogated parallel belts according to geological, geomorphological and hydrological characteristics. They are, first, the littoral Karst or Periadriatic Karst, second, the Karst of Notranjsko or High Karst, and third, the karst of Dolenjsko or Peripannonian Karst. On a small scale different morphological units alternate in longitudinal Dinaric zones.



A Alpine karst
B Dinaric karst: 2 - Low Littoral karst
3 - High karst of Notranjska and Dolenjska
4 - Low karst of Dolenjska and Bela krajina
5 - High karst on dolomite
C 6 - Isolated sub-Alpine and sub-Dinaric karst
7 - Fluvial surface with underground out-flow through karst
8 - Karst polje, bigger karst depression

Figure 1 *Karst in Slovenia (P. HABIC, 1992a)*



1- higher conical karst
2- karst margin plains and pediments
3- lower karst plains
4- lowered surface with karst plains
5- karst poljes
6- contact fluviokarst
7- fluvial relief encircled by karst
8- litoral tectonic karst scarp

Figure 2 *Geomorphological classification of NW Dinaric karst (P. HABIC, 1991)*

The Littoral karst extending along the Adriatic coast is further divided into original Kras area (called also *Trzaski Kras* or *Trieste Karst* or *Carso di Trieste*) in the background of the *Timavo spring*, and, second, the karst of northern Istria, i.e. the *Materija dry valley* and the *Slavnik mountains* in the background of the *Rizana* and *Osp karst springs*. Classical Kras is built of Cretaceous limestones and dolomites, Paleocene limestone and Eocene flysch. In Neogene these series were folded and faulted. Rivers from Vipava flysch rim and the surface flowing *Notranjsko Reka*, draining till now the flysch of the *Brkini mountains* in the southeast, have downcut wide dry valleys and karst plains in the Classical Kras. D. RADINJA (1972) found the rest of gravel accumulation of neogene rivers. The brooks from Mts. Brkini have eroded 12 blind valleys on the southern footslope (I. GAMS, 1962).
The longest blind valley is that of the *Notranjska Reka - Vremska dolina* with its terraced bottom (D. RADINJA, 1967). The river Reka sinks in the caves *Skocjanske jame*. There are two fresh collapse dolines and many older collapse dolines there. The Skocjanske jame present the biggest natural curiosity of the whole Classical kras, they make part of the typical morphogenetical unit of contact karst, unique in Europe regarding its phenomena

and dimensions. The natural reserve Skocjanske jame and the vicinity was listed in 1986 as natural and cultural heritage of the world at UNESCO as the example of caves of extreme dimensions and karst landscape with rich history and interesting cultural traditions. By gradual karstification starting after erosional or tectonical lowering of impermeable flysch border of Kras, the valley of the Reka incised more and more. At the ponors into the surface under 450 m a.s.l. a blind valley, 130 m deep, 5 km long and up to 2 km wide, was cut in four terrace levels. The actual Reka ponor lies under 108 m high wall of Skocjan on 317 m a.s.l. The entrance passage is narrow and high, developed along a bigger fissure therefore the passages reach 50 to 80 m. The axis of Skocjanske jame is presented by 2,5 km long underground canyon which has no lateral active water channels, at the end of which a deep explored syphon exists. Underground continuation of the Reka between Skocjanske jame and 8,6 km long Kacna jama near Divaca is unknown on the distance of 1500 m. Unknown is also the underground flow between *Kacna jama* and the 30 km distant *Timavo springs*. With its dry higher channel rich in speleothem, with its mighty huge water channel, with its archaeological and biological importance this cave is besides the Postojna cave, the greatest jewel of the Slovenian karst, which is not yet fully appreciated in tourism. Cave research organizations of Slovenia have till now registered more than 700 caves and potholes in the area of ca. 500 sq. km of the classical Kras, but over 6500 caves are known in whole Slovenian karst.

The **Karst of Notranjsko** (*Inner Carniola*) belongs to the central highest Dinaric belt and is separated from the Littoral Karst by a narrow belt of impervious Eocene flysch. High, wooded and scarcely populated karst plateaus at an altitude of 800 to 1700 m with intermediate lower valley-like karst depressions at an altitude between 400 and 600 m are predominant in this area. The karst is developed primarily on Triassic, Jurassic and Cretaceous limestones and dolomites but there are also small sections of impervious marls, sandstones and schists that divert the surface waters and dam the underground waters and thus influence the formation and the layout of the through-flow karst. The high out-flow karst can be subdivided in relation to structural tectonic and morphogenetic characteristics into the following more or less coherent hydrogeological units: *Banjsice, Trnovski gozd, Hrusica, Nanos, Javorniki, Sneinik, Krim, Velika gora, Kocevski Rog* and the central part of the Gorjanci mountains. Karst waters flow out from these units to several directions and feed the karst springs in their border zones.

Lying between these high areas of out-flow karst is the central part of the through-flow karst of Notranjsko. Across it the surface and underground waters flow forming intermittently flowing streams that flood the karst poljes. A considerable part of the through-flow karst belongs to the drainage basin of the Ljubljanica river, but some waters drain also towards the rivers *Kolpa* and *Krka*. There is a string of karst poljes in the upper reaches of the Ljubljanica including *the Prezid*, *the Babno polje*, *the Rakitna*, *the Bloke*, as well as better known *the Loz*, *the Cerknica, the Planina* overflow poljes, *the Logatec* contact polje and *the Pivka basin*. The main springs for these waters are located along the western fringe of *Ljubljana moor* (P. HABIC, 1982). There is the famous *polje of Cerknica* with its periodic lake, numerous springs on the southeastern and ponors in the central part and in the northwest side. In the year 1971 a sluice was built at the entrance of *the ponor* *cave Karlovica* which has prolongated the lake phase from 6 to 7 months yearly. The purpose of that is to intensify the lake fishing and tourism. The alternation of the dry and the flood phases, which was in early modern times a matter of admiration for so many scientists still persists (I. GAMS, 1974).

In the Notranjsko podolje only the polje of Postojna - Pivka has bigger flysch area. The rivers draining the flysch have shaped many caves in Cretaceous limestone. The longest is *Postojnska jama* (19,5 km) which is the most visited European cave (since the discovery in 1818 more than 25 million of tourists). Other active caves are situated on the outlet side of the poljes (*Predjama* 7,5 km, *Karlovica* 7,3 km, *Tkalca jama* 2,8 km, *Najdena jama* 5 km, *Logarcek* 2,3 km, *Krizna jama* 8,1 km), rarely on the spring side (*Planina* 6,1 km, *Zelske jame* 3 km). The triangle territory among Postojna, Loz and Logatec on the 30 sq. km has 60 km long cave channels and this is the greatest cave density in Slovenia (I. GAMS, 1974; P. HABIC, 1982a).

The karst of Dolenjsko (Lower Carniola) belongs to the shallow out-flow through-flow karst of the inner Dinaric or Peripannonian belt. The surface is covered with thicker layer of the red karst soil, typical terra rossa, that has made possible denser population in more continuous tracts of agricultural landuse. Gentler forms, dolines, uvala like depressions, even small karst poljes and rounded hills, are predominant in the karst relief. Waters derive from the impervious and dolomitic rims of the karst areas and flow only at small depth under the surface or even in shallow open canyons.

c) **The isolated karst** in sub-Alpine and sub-Dinaric Slovenia is subdivided according to the geological, orographical and hydrographical characteristics into several homogenous isolated units. The hydrological significance of the isolated karst depends on the location and size of carbonate rocks. Both, the shallow and the deep, the out-flow and through-flow karst can be found in this part of Slovenia just as the impounded karst with syphons and the dome karst with the gravitational drainage on the underground waters.

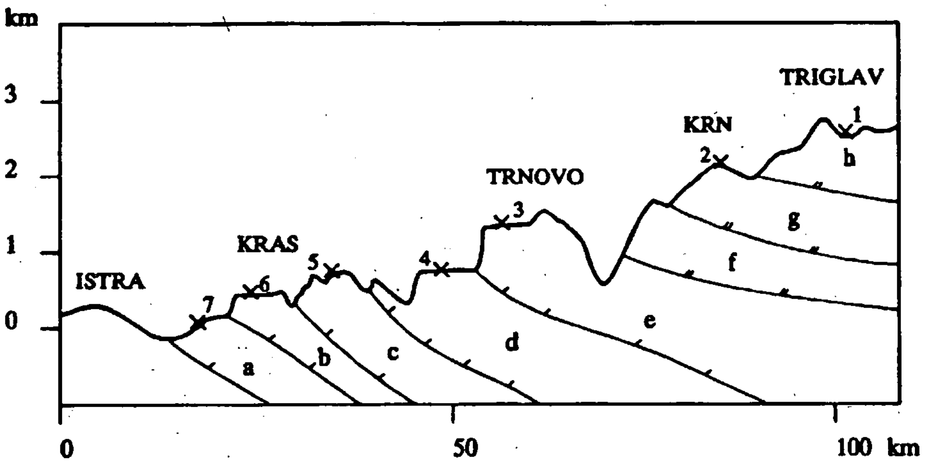
GEOMORPHOLOGICAL DEVELOPMENT OF THE DINARIC KARST

Morphological units accord nearly completely with structure units. In relief the structure got the greatest importance at the contact of permeable and impermeable rocks (contact karst) but also in disposition of singular shapes of relief on the karst surface (structural karst). In Eocene flysch and in Triassic shales and Permian sandstones erosion lowered the surface faster and was generally more efficiate than corrosion on the karstic areas. When calcareous regions were eliminated by tectonic degrees from general fluvial transformation, differences between karst and impervious regions increased. And so the following karstic evolution depended chiefly on different climatic conditions in particular periods.

Cone or stack-shaped karst hills are characteristic for the central highest part and we can range them in singular level with altitudes. Levels of stackshaped hills surprisingly accord also in different structural units, about which older geomorphologists throughout they are unequally dislocated with younger tectonic removals (A. WINKLER, 1957).

Dissection of relief in higher regions call the attention to particular morphogenetic processes, which succeeded in parcelling out the former surface into the relief of stack-shaped hills and closed dry valleys. Disposition of these forms do not accord with normal fluvial transformation, but to a large extent refer to the structure and karst dissection. According to the model and disposition of karst hills we can conclude that karst evolution of the central part of the High Karst began in close connection with climate condition in warm and moisten middle Pliocene or even Miocene era.

In the next phase of morphological evolution, flattenings predominated in border parts of the High Karst and so enormous pediplains sprang up in altitude about 800 and 900 m. On flat surface there are preserved rare isolated hills only, typical hums, which are characteristic also for similar karstic regions in lower Dinaric Karst. Remains of fluvial gravel on border plateaus of the High Karst prove very well that this area originated under the influence of surface running waters, which could periodically transport sand and gravel from impermeable border (P. HABIC, 1992).



Over-thrust units

a - Koper
b - Komen
c - Sneinik
d - Hru"sica
e - Trnovo
f - Kobla-Rut-Podmelec
g - Krn-Savinja
h - Triglav

Paleokarstic

1- Kredarica-Rz-Planika
2- Lanzevica-Gradic-Podrta gora-Krosnja
3- Lokavec
4- Nanos-Hrusica
5- Postojna-Pivka
6- Koblak-Fernetici
7- Crnotici

Figure 3 *Paleokarstic phenomena on the Slovenian karst (P. HABIC, 1992)*

Then followed a new phase in the development of the karst relief. On the borders of High karst intensive deepening of valleys predominated in impermeable areas. Carbonate regions were by degrees completely eliminated from transversal and border fluvial transformation. Karstic dissection did not begin at once in entire actual karst area. The highest karst regions are normally the oldest, and they were exposed to the greatest climatic changes, from wet warm to real mountainous climate.

The highest step formed relief is dissected into stack-shaped summits and into larger, gently or steep sloping dolinas - kontas. They are most frequent in the highest central Dinaric ridge, over 1200 m a.s.l. In the bottom of some kettles or "kontas" there are entrances into ice-caves and deep abysses, some among them surpass direct vertical of 200 m, and total deepness of 50 m.

Among the greatest karstic depressions in the highest part of High Karst belong kotli, doli and drage, depressions with diameter between 0,5 and 1 km, and depth from 100 to 300 m (Table 2). They are disposed at greater fault lines and very often on the limit between limestone and dolomite. In their deepening, accumulation and melting of ice had great importance, because all these depressions began on the limit between glacial and periglacial zone in cold periods of Pleistocene. Accumulation of ice is testified by moraine material that is still preserved in the bottoms and on the borders of mentioned depressions. Characteristic for these depressions is also temperature and vegetation inversion, which is accelerated not only by big altitude of 1250 m a.s.l. but also by karstic cavernosity with comparatively low summer temperatures and winter accumulations of snow.

In lower border plateaus and pediplains karstic transformation began later than in central part of High Karst. At first karstification advanced under fluvial sediments, progressively sand, gravels and also clays were eliminated and processes that are characteristic for bare karst predominated. In drought and warm periods, when calcareous surface was still covered by sands and clays, shallow and broad piedmont uvalas arose. After removal of sediments, especially in cold and wet periods of Pleistocene, local deepening of karst relief predominated. In uvalas and on the flat surface dolines began to rise, which are younger than uvalas and they do not follow evolutive form, originating on the junction with dolines, according to J. CVIJIC (1960).

In Periglacial zone fine formation of surface was important under the influence of frost and corrosion of bare rock. By formation of limestone pavement in this phase of karstic transformation also differentiation in relief is important, first of all owing to petrographic differences among limestones and especially among dolomites. Development of structural karst forms was accelerated in cold humid periods.

Post glacial corrosion transformation of karstic area covered with vegetation did not completely succeed in eliminating the traces of Würm high mountainous karst. Essential traces of former surface are preserved either in big, with periglacial and glacial material filled karstic depressions, where only smaller alluvial dolines are formed now, or in differently preserved limestone pavements where we can study the entire evolution of their destruction.

Consequently, relief of high Dinaric karst is the result of different transformation processes which made their influence felt from time in the Mio-Pliocene to geological present. Singular relief properties are due to climatic conditions. In warmer subtropical

Pliocene climate mostly plains, cone-shaped surface and karst poljes could originate. Cooler Pleistocene climate contributes to karst dissection by kettles, dolines, limestone pavements and thin superficial down cuttings. But only fluvial erosion-corrosional and climatically conditioned processes cannot explain all the relief properties of Dinaric Karst. Geostructural conditions and differentiated tectonic movements of particular geoblocks have to be considered too, forming particular morphotectonic units.

GEOMORPHOGENETICAL INTERPRETATIONS

Geomorphogenetical studies accentuated the successive development phases and prevailing processes as they could be noticed on the karst surface. Superficial transformation elapsed in relatively long post Eocene orogene period. Several epirogenetic phases followed when the rate between permeable and impermeable rocks changed considerably.

Post-over-thrust radial tectonics cut folded and thrusted rocks into big blocks and differently uplifted them. Erosion, that followed, removed thick layers of softer and more resistant rocks as well as the actual surface comprises different structural units and rarely corresponds to them. In general the surface on the impermeable rocks is more lowered and erosionally more dissected than on limestones or dolomites. The inverse altitude ratio is extraordinary. The impermeable areas controlled by normal superficial drainage are more lowered than the ones draining through the karstified borders.

In the inliers of impermeable rocks in the middle of the karst normal fluvial relief with local erosional base in the altitude of shallow-holes developed. Somewhere along them either smaller or bigger karst depressions, blind valleys and poljes appear, or the allochthonous superficial rivers cut their canyon-like beds in the karst surface. Different types of contact fluvio-karst were formed (I. GAMS, 1986).

Recent regional climatic conditions importantly controlled the genesis of the surface. They are evidenced in locations exposed to sun or sunless and in different altitudes above the sea, on the passage among mediterranean, submediterranean and continental mountain climate in particular. Morphological differences were carried into effect in cool Pleistocene conditions mostly, when the areas above 1300 m were permanently covered by snow and ice, and the surface above 600 m was bare as it is today above the upper forest line in the altitudes between 1600 and 1800 m.

Lower submediterranean areas are warmer and less wet, mean annual temperature above 10 °C, 500 to 1000 mm of rainfall, seldom in form of snow. On the highest ridges of Dinaric karst the mean annual temperatures are 5 °C with more than 3000 mm of rainfall, snow prevail in cooler half of the year, it can last from October to May, the blanket of snow is 1 to 2 m thick. High intensiveness of rainfall is morphologically important as more than 300 mm could fall in one day even. All the rainwater sink directly into karst. Superficial drainage relates to less permeable rocks, distributed among. the limestones as partial or complete border or hanging hydrogeological barriers.

CORROSION INTENSITY

A lot of water contributes to intensive solution, lowering the karst surface from 30 to 150 mm in thousand years in average. In spite of different methods defining the corrosion intensiveness the values presented on the following table correspond well.

region	river basin	denudation rate (mm/1000 years)
Litoral karst	Vipava source	82 * 68 **
High karst	Hotenjka Idrijca, Idrija Podroteja Trebusa Ljubljanica	126 * 157 * 90 ** 90 * 65 *
Lower karst	Krka, Dvor	33 **

* - HABIC, 1968, pg. 21 ** - GAMS, 1966, pg. 54

Table 1 *Corrosion intensity in Slovenia*

Local corrosion effects do not depend on lithological base only but on pedo-cover, vegetation, altitude above the sea level and other factors (I. GAMS, 1992) among which the way of vertical percolation too. Infiltrated water joins into trickles and flows through crushed or less impermeable zones. The trickles are either permanent or periodical of various discharge. The rate between low and high discharge and between small and big trickles is 1:10.000 and more (P. HABIC & JANJA KOGOVSEK, 1979). The consequences of different washing off reflect in intensive karst dissection on the surface. In climatical and energy sense it is more intensive in higher than in lower positions. The dissection of higher karst is not due to solute processes only, but to mechanical weathering of limestones and dolomites in particular as well as to sheet erosion of the scree from the slopes into closed karst depressions or into hanging gullies.

The size of karst dolines on the chosen morphological unit from Sneinik, 3 times 4 km, is presented on the table 2.

type of doline	number	diameter (m)	depth (m)	surface in 10^3 m^2	volume in 10^3 m^3
A snow doline	124	10	5	0,3	0.5
B doline	57	25	10	2	6.5
C small kettle	34	50	20	8	50
D medium kettle	28	100	30	30	300
E big kettle	16	200	50	125	2000
F double kettle	1	400	80	500	13000
M.Ponikva, Bakar*	1	1000	150	600	30000
V.Ponikva, Bakar*	1	1400	180	1200	72000
Praprotna draga*	1	2000	210	6000	150000

* comparative size of the biggest depressions in the high karst

Table 2 *Number and size of karst dolines on Sneinik mountain*

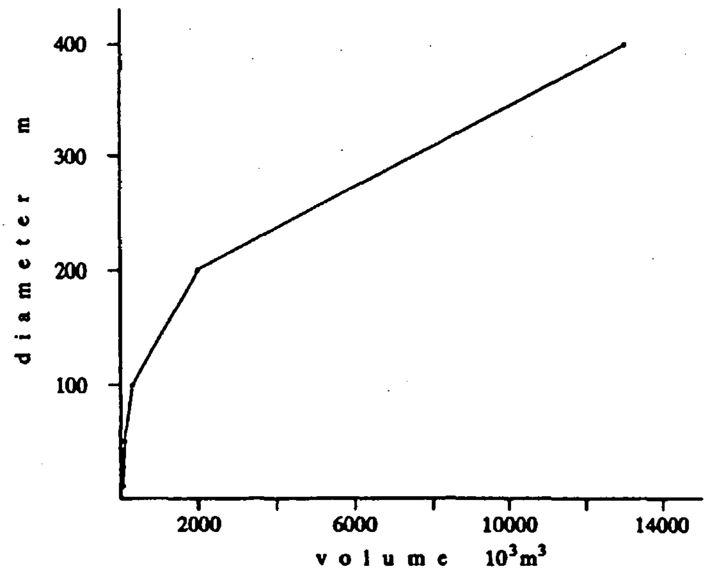


Figure 4 *Karst dolines in High karst (Sneinik mountain): relation between diameter and volume*

CONCLUSION

The geomorphogenesis of the Dinaric karst in Slovenia is based on previous knowledge about the origin and development of Classical Karst. According to relief, hydrographic and speleological properties the area became famous in past century. Geomorphologists J. CVIJIC, A. MELIK, J. ROGLIC and I. GAMS studied it among the others. They were followed by younger researches who deepened their knowledge by new results.

Today we think that he surface among Tertiary Pannonian basin, Alps and Adriatic Sea was formed some time about the Pliocene onwards. First deciding factors were morphogenetical influences from the impermeable vicinity when the waters ran off superficially over the impounded carbonate rocks. Later tectonical movements contributed to surface transformation and to karst dissection, dismembering and differently uplifting the particular carbonate blocks. geological basement including differently resistant lithological links and tectonically broken rocks played an important role while shaping their corrosional and erosional relief. Beside the above mentioned factors, climatically controlled processes in Tertiary and Quaternary transformed the karst relief significantly. Their influences are seen in the distribution of conical-shaped hills, wide pediments, karst peneplains, poljes and uvalas, deep dales, kettle-funnelor dish dolines and thinly corroded surface. Geomorphological influences from the impermeable vicinity are preserved in forms of contact fluviokarst, in canyon, steep-head and blind dolines and in the remains of fluvial or marine sediments, loam, sand and gravel which are preserved on the karst surface and its underground.

According to the predominating relief properties the NW Dinaric karst is divided to three basic morphogenetical units and the division continues to smaller parallel dinarically oriented stripes which are mainly tectonically conceived. Each unit distinguishes by singular complex of karst forms.

REFERENCES

BRODAR, S., 1952: Prispevek k stratigrafiji jam Pivske kotline, posebej Parske golobine. Geografski vestnik, 24, 43-76, Ljubljana

CVIJIC, J., 1893: Das Karstphänomen. Geogr. Abh. 5, H. 3, 217-329, Wien

CVIJIC, J., 1918: Hydrographie souterraine et évolution morphologique du karst. Recueil de travaux de l'Institut de Geographie Alpine, 6/4, Grenoble.

CVIJIC, J.,1960: La geographie des terrains calcaires. Monographies, CCCXLI, Classe des sciences mathematiques et naturelles, 26, 1-212, Beograd

FORD, D. & WILLIAMS, P., 1989: Karst geomorphology and hydrology. Univ. Press, Cambridge

GAMS, I., 1962: Slepe doline v Sloveniji. Geogr. zbornik, 7, 263-306, Ljubljana

GAMS, I., 1965: Types of Accelerated Corrosion. Problems of Speleological Research, 133-139, Praha

GAMS, I., 1974: Kras. Zgodovinski, naravoslovni in geografski oris. Slovenska matica, 360, Ljubljana

GAMS, I., 1985: Mednarodne primerjalne meritve povrsinske korozije s pomocjo standardnih apneniskih tablet. Razprave IV. razreda SAZU, XXVI, 361-186, Ljubljana
GAMS, I., 1986: Kontaktni fluviokras. Acta Carsologica, 14-15, 71-87, Ljubljana
GAMS, I., 1992: Les influences des climats dans les régions karstiques. Press. Univ. de Bordeaux, 411-428, Bourdeaux
GOSPODARIC, R., 1976: Razvoj jam med Pivsko kotlino in Planinskim poljem v kvartarju. Acta Carsologica, 7, 5-135, Ljubljana
GOSPODARIC, R., 1986: O geoloskem razvoju klasicnega krasa. Acta Carsologica, 14-15, 19-29, Ljubljana
HABIC, P., 1968: Kraski svet med Idrijco in Vipavo. Dela Instituta za geografijo SAZU, 21, 239, Ljubljana
HABIC, P.& KOGOVSEK, JANJA, 1979: Percolating water karst denudation in the case of Postojnska and Planinska cave. Actes du Symposium Intern. sur l'erosion karstique U.I.S, 49-60, Aix en ProvenceMarseille-Nimes
HABIC, P., 1982: Kraski relief in tektonika. Acta Carsologica, 10, 23-44, Ljub.
HABIC, P., 1982a: The hydrogeological differentiation of karst areas in Slovenia. Geogr. Iugoslavica, 3, 52-29, Ljubljana
HABIC, P.et al., 1990: Izviri Doblicice in njihov krasko zaledje. Acta carsologica, 19, 5-100, Ljubljana
HABIC, P., 1992: Les phenomenes Paleokarstique du karst Alpin et Dinarique en Slovenie. Karst et évolutions climatiques. Press. Univ. de Bordeaux, 411-428, Bourdeaux
HABIC, P., 1992a: Kras and karst in Slovenia. Slovenia. Geographic aspects of a new independent European nation. The Ass. of Geogr. Soc. of Slo., Ljubljana
HERAK, M., 1977: Tecto-genetic approach to the classification of karst terrains. Krs Jugoslavije, 9/4, 227-238, Zagreb
MELIK, A., 1935: Slovenija. Geografski opis, 1. knjiga, Slovenska matica, Ljub.
MELIK, A., 1955: Kraska polja Slovenije v pleistocenu. SAZU, razr. 4, 7, Lj.
MELIK, A., 1961: Fluvialni elementi v krasu. Geogr. zbornik, 6, 333-362, Ljubljana
MELIK, A., 1963: O dolih na krasu. Arheol. vestnik, 13-14, 223-240, Ljubljana
RADINJA, D., 1967: Vremska dolina in Divaski kras. Geogr. zbornik, 10, 157-269, Ljubljana
RADINJA,D., 1972: Zakrasevanje v Sloveniji v luci celotnega morfogenetskega razvoja. Geogr. zbornik, 13, 197-243, Ljubljana
RENAULT, Ph., 1992:
ROGLIC, J., 1957: Quelques problèmes fondamentaux du karst. L'Information geographique, 1, 1-12, Paris
ROGLIC, J., 1960: Das Verhältnis der Flusserosion zum Karstprocess. Zeit. für Geomorph., 4(2), 116-138, Berlin
ROGLIC, J., 1965: The delimitations and morphological types of the Dinaric karst. Nase jame, 7, 12-20, Ljubljana
SIFRER, M., 1990: Razvoj reliefa na Slovenskem v luci klimatske geomorfologije. Geomorfologija in geoekologija, 45-54, Ljubljana
WINKLER, A., 1957: Geologishes Kräftenspiel und Landformung. Wien

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HIGHLIGHTS ON DOLINE EVOLUTION

Ugo SAURO

ABSTRACT

The dolines are originated by accelerated corrosion in connection not only with surface overland flow but also with the evolution of gradients of hydraulic conductivity inside a shallow limestone "zone," called "epikarst".

If the hydrological model based on the focusing of solution process is clear, it does not explain all the aspects of doline evolution.

In fact a lot of questions emerge from the field analysis of the dolines.
For example we may see that very small dolines are lacking in most of the doline populations and that often dolines begin to develop very near to the contacts between a caprock and a limestone rock unit or between a marly limestone rock unit and a pure limestone rock unit.

The interference between fluvial, slope, glacial and periglacial processes may interfere with doline evolution.

To solve the morphogenetical problems of dolines we must consider, not only the surface form, or "epiform", but all the doline structure from the epykarst to the interface soluble rock - filling deposits, to the soil cover.

It is possible to verify that in the first stages dolines often evolve as "cryptoforms", before to become epiforms. After they have become epiforms they act as traps for sediments both local and allogenic. So their evolution and history may be very different according to structural control, hydrological and environmental characters and changes.

RIASSUNTO

Le doline sono originate dalla corrosione accelerata in relazione non soltanto con il ruscellamento superficiale ma anche con l'evoluzione di gradienti di conduttivitê idraulica all'interno dalla zona carsificata piu superficiale, datta "epicarso"..

Tuttavia, anche se il modello idrologico sulla focalizzazione dei processi di soluzione puo dirsi soddisfacente, esso non basta a spiegare tutti gli aspetti dell'evoluzione delle doline.

Dalla ricerca sul terreno emergono molti problemi.

Tra l'altro noi constata che nella maggior parte delle popolazioni di doline mancano le forme di piccole dimensioni e che spesso le doline si sviluppano in prossimitê del contatto fra formazioni con caratteri diversi ed in particolare fra "caprocks" e calcari o fra calcari marnosi e calcari puri.

Con l'evoluzione delle doline possono intereferire anche processi fluviali, di versante, glaciali e periglaciali.

Per risolvere i problemi dell'evoluzione morfologica delle doline occorre considerare, oltre alle condizioni ambientali, non soltanto la forma superficiale, ma l'intera struttura della dolina dall'epicarso, alle interfaccie fra la roccia solubile e i depositi di riempimento ed il suolo.

E' possibile verificare chè negli stadi iniziali la dolina spesso si evolve come una "cryptoforma", prima di divenire una "epiforma". Dopo essere divenuta una epiforma essa agisce come una trappola per i sedimenti sia locali, sia allogenici. La storia evolutiva puij essere molto diversa in relazione all'influenza della struttura ed ai caratteri ed ai cambiamenti idrologici ed ambientali.

THE SOLUTION DOLINES

The doline is the most specific surface form of karst landscapes. The more common type of doline is the solutional one, which is an elementary hydrographic unit, comparable with a valley of the fluvial landscape.

Analogously with the valleys the dolines present a large variety of typologies in spite of the seeming dullness of the forms, as a wide range in size (from a few meters to about one kilometre in diameter and from a few decimeters to more than 100 meters in depth), and a great diversity of shapes.

Even if tens of Authors have written about dolines, the evolutionary aspects of these forms need supplementary research.

After GAMS (1974) dolines are originated by accelerated corrosion; WILLIAMS (1985) has illustrated a hydrological model of doline evolution, based on the development, by solutional processes, of gradients of hydraulic conductivity inside a shallow limestone "zone," called "epikarst," just below the soil surface.

These two alternative models may fit together, but they don't explain some peculiarities of these forms as, for example, why only very few small forms, interpretable as embryonic stages (dolines of few meters in diameter and few decimeters in depth) are recognizable on the field; and why there is a so large variability in doline characters.

From now on, some outstanding questions follow population of dolines:

1) Why very small dolines (a few meters in diameter) are lacking in most of the populations dolines?

2) Why some populations of dolines begin to develop very near to the lithological (both stratigraphical or tectonic) contacts between a caprock and a limestone rock unit or between a marly limestone rock unit and a pure limestone rock unit?

3) Why and how some fluvial valley bottoms begun to evolve as chains of dolines?

4) Why and how some large forms, as the glacio-karstic depressions, are of complex origin?

5) How dolines act as traps of sediments and what are the main consequences of the sedimentary fillings?

If we could answer to these questions we will probably solve the main problems that arise from the geomorphological studies on the field.

THE PUZZLE OF LACKING OF SMALL DOLINES

Most of the doline populations are lacking of small forms, less than 10-15 m in diameter. In fact it is impossible to found them on large scale maps, on aerial photographs and directly on the field (*Fig. 1*).

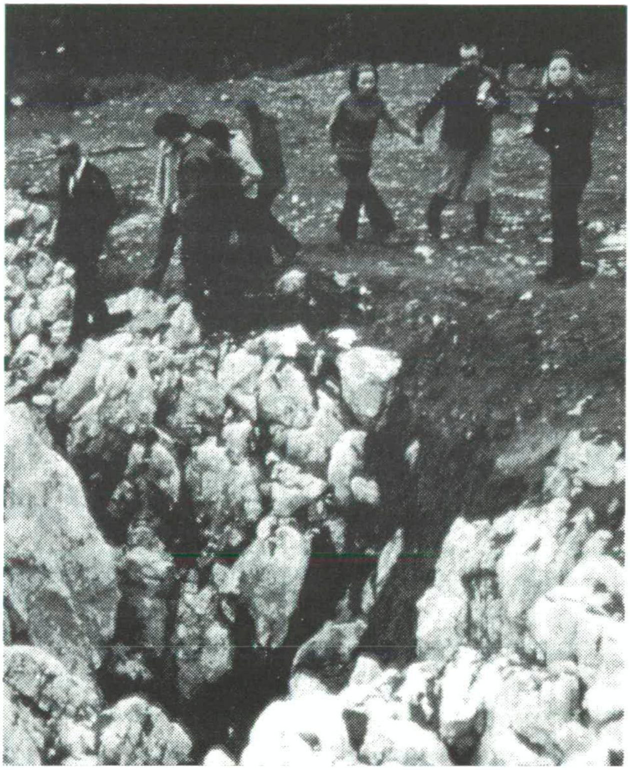


Figure 1 *Cryptodoline cleared by soil fillings in a quarry near Vrhnika (Slovenia). Near the forms is recognizable Prof. Ivan Gams* (photograph taken by Sauro in 1974).

This is curious if one thinks that medium size dolines should have developed from smaller forms and that consequently a nearly continuous series of forms should exist. Good examples of this situation are the Classical Karst of Trieste and the karst in conglomerate rocks in Montello (Venetian Fore-Alp, Italy).

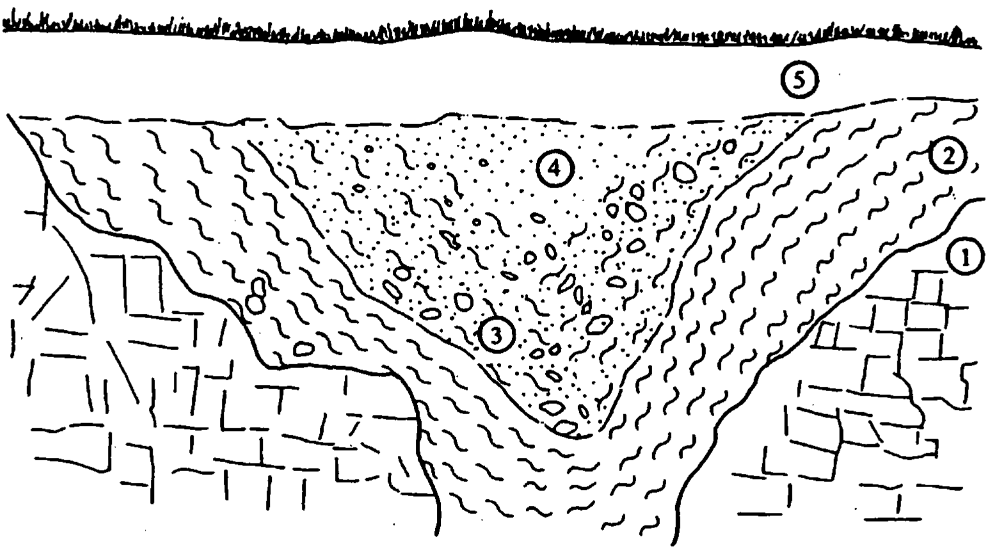
The only small doline-like forms exist:

- as fissure like, or subcylindrical hollows;
- on loose deposits because of suffusion or sediments "subsidence";
- as field of small conical dolines in halite karst and in some gypsum karst;
- as funnel shaped depressions along some active faults with evidence of surface faulting;
- as craters resulting from bombs.

If one goes to see the artificial cuttings in the quarries or along new routes it is possible to observe that the smaller karst depressions are filled by debris and soil sediments. Many dolines become to exist as "cryptokarstic structures" before to become surface forms. The first Author who has underlined the importance of cryptokarst is NICOD (1975).

THE CONTACT DOLINES

The influence of the lithology and of the geologic structure on doline evolution is clear where there is a stratigraphic or tectonic transition between dissimilar permeable rocks with different hydraulic behaviour. It is well known that dolines and shafts often develops near the contact between a caprock and a karstifiable rock unit (*Fig. 2*). Field of dolines of this type are well known in Mammuth Cave National Park (Kentucky, USA).



1=bedrock constituted by a marly limestone, 2=mostly clay "terra rossa" paleosol, 3=silty "terra rossa" paleosol, 4=loess like silt, 5=active soil

Figure 2 *Section of a cryptodoline in an artificial cutting in the Lessini Mountain (Venetian Fore-Alps).*

Very interesting examples are in the Lessini Mountains (Venetian Fore-Alps, Italy), where most of the dolines are to be found near the stratigraphic or tectonic transition between of whitish marly limestone closely stratified and densely fractured ("Biancone" of Lower and middle Cretaceous) and a more pure and massive limestone with less dense and more extensive fractures ("Rosso Ammonitico" and "Calcari Oolitici" rock units of Jurassic Period). Here the dolines occupy well defined morpho-structural positions (SAURO, 1973, 1974) as:

- Infacing slope dolines and shafts;
- "Rosso Ammonitico" structural surface dolines and shafts;
- Fault-line dolines and shafts;
- Valley bottom dolines in the lower Biancone.

Doline evolution seems linked with the downward transition from a subhorizontal circulation (aquifer levels in a small lithoclastic network) to an essentially vertical one (diaclastic circulation) from the marly and more fractured limestone to the underlying and/or adjacent more pure and fewer fractured limestones.

In the erosional transition between the two types of rock units doline morphogenesis is preceded by the development of peculiar epikarstic structures controlled by the lithological and structural transition.From the hydrological point of view these dolines represent an intermediate situation between the "point recharge dolines" and the "drawdown dolines" of FORD & WILLIAMS (1989).

CHAINS OF DOLINES THAT MARK THE DEATH OF A FLUVIAL VALLEY

The more common example of interrelation between karst and non karstic processes in dolines evolution is to be found where doline evolution follows a phase of fluvial morphogenesis.

In the evaporitic karst in west Sicily (Southern Italy) a valley pattern developed in the impermeable covers has been inherited by a soluble gypsum rock unit (AGNESI & alii, 1989). Here dolines development occurs on the valley bottoms, beginning from the earliest swallow which acts as "point recharge hollow." Each valley becomes a blind fluvial-karstic closed depression. In the time new and more active swallow-holes develop upstream. So chains of "point recharge" dolines are recognizable with their bottoms upstream at a progressively lower altitude. These forms are also common in limestone (good examples are to be found in the Bucham karst, Victoria, Australia).

If a network of fluvial valleys, cut in a not karstic rock unit, begins to dissect karstic rocks, karst processes cause a loss of water on the valley bottoms till to a complete "drying" of the surface streams. The dried valley pattern inherited by the karst rocks continues to evolve because of the chemical solution of the valley bottoms, accelerated in comparison with the slopes and the ridges. If dispersed infiltration and large debris accumulation occurs, as in some dry valleys of the Venetian Fore - Alps, very few dolines develop. These forms evolve especially where concentrated water percolation occurs (*Fig. 3*).

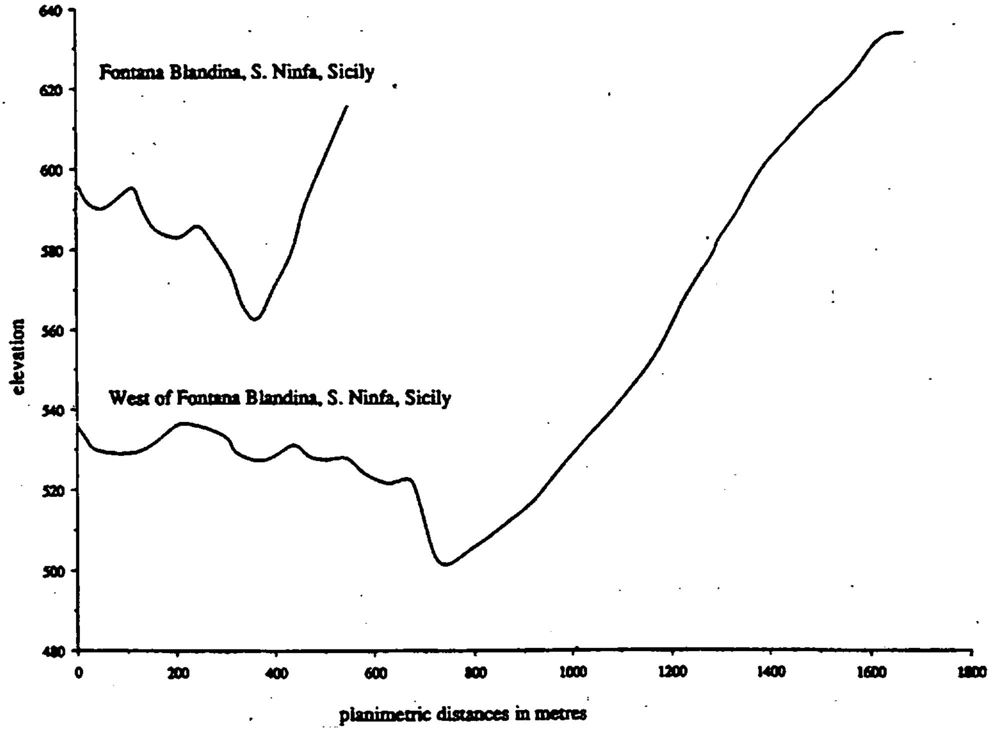


Figure 3 *Profiles of chains of "point recharge dolines" formed along valleys in the evaporite karst of Santa Ninfa in western Sicily. The bottoms upstream are at a progressively lower altitude. The vertical exaggeration is of 7,7.*

OTHERS MIXED, POLYGENETIC AND POLYPHASIC ORIGIN CLOSED DEPRESSIONS

The chains of closed depressions along the bottom of a previous fluvial valley are of mixed origin: fluvial and karstic.

In mountain environment it is possible to find other types of depressions of mixed origin. The more typical are the glacio-karstic depressions formed by an alternation of glacial and karstic processes. Some of these depressions are on the bottom of a glacial cirque, others on plateau surfaces are developing in their upper parts as small glacial cirques. Apparently sometimes glacial cirques have preceded dolines, in others dolines have preceded glacial cirques.

DOLINES AS TRAPS

In the middle latitude karst, doline evolution is linked, beside with the karst denudation, with others weathering processes working on the slopes and with fillings deposition inside the closed depressions by soil sediments, periglacial scree deposits, loess like deposits, and sometimes by glacial deposits and by volcanic ashes. In many areas fillings from a few meters till to some tens of meters have been recognized (MAGALDI & SAURO, 1982, ZAMBO, 1985).

In Monte Baldo (Venetian Fore-Alps) a large variety of dolines are present:

- dolines with flat, horizontal and very large floors; with a marked difference between minimum and maximum depths (difference between the highest and lowest points the perimeter with respect to the floor of the depression);
- dolines with small "terraces" in their interiors, with respect to which one or more funnel shaped depressions are placed;
- "open dolines" with a flat horizontal floor not completely surrounded by slopes (here minimum depth is zero and the doline is recognizable by the half amphitheatre shape of the slopes);
- "opened dolines" with no flat horizontal floor, consisting of bowl shaped depressions with one side dissected by a small valley.

Sometimes the filling deposits have nearly completely obliterated an older karst relief, consisting in large depressions, and favoured the development of clusters of smaller depressions inside the ranges of the old ones. Many more recent smaller dolines are found grouped inside the relicts of these "paleo-forms".

The filling deposits of the higher area are mainly composed of rather angular limestone fragments varying in their diameters from a few centimetres to some decimeters and embedded in yellowish silt.

The current karstic forms are masked by deposits that have filled the original dolines sometimes to the rim.

If we search to reconstruct the landscape evolution we may suppose the alternation of three main types of morphogenetic phases, occurred in different environmental conditions:

- in a warm and humid climatic phase, evolution of a karstic relief composed of more and less cone-shaped hills with large, deep dolines (now mostly dismantled and generally hard to distinguish);
- in periglacial conditions relief dismantling and filling of the karst depressions by aeolic loess and by angular fragments produced by cryoclastic dismantling of the ridges between the dolines;
- in temperate and humid conditions, which may be referred to interglacial periods, intense karstic morphogenesis.

Some very interesting examples of doline evolution are to be found also in the Velebit Mountains, where at least two different models are distinguishable.

In the central plateau very large, deep funnel shape dolines exist, nearly without slope covers and filling deposits inside. In the southern Velebit the dolines are much more similar to those of M. Baldo.

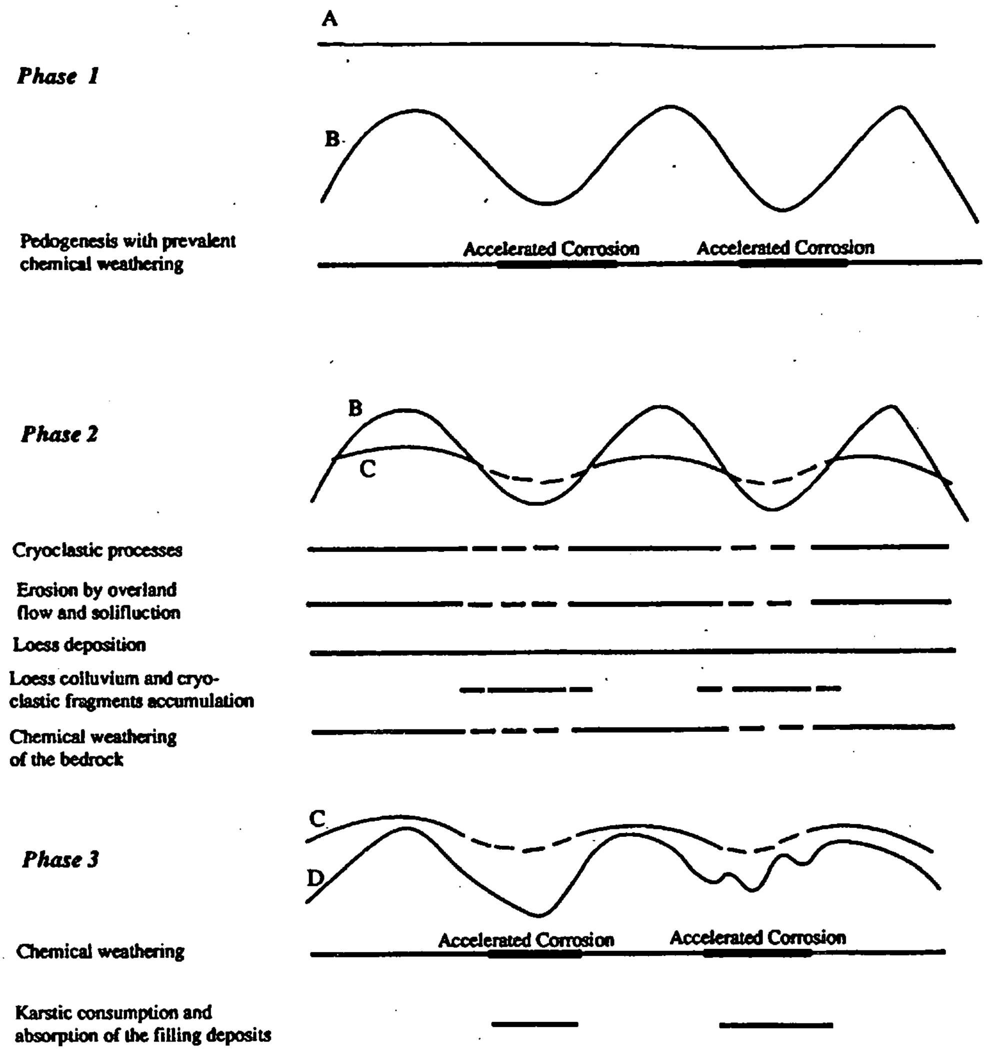


Figure 4 *Diagram illustrating the sequence of different phases of doline relief evolution in Southern Monte Baldo plateau* (Venetian Fore-Alps, Italy) *and the role of different erosional and depositional processes.*
After an initial phase of karstic morphogenesis on limestone without detritic cover, alternate phases occurred, with dismantling of karstic relief in periglacial conditions (type 2), and karstic erosion on an originally complex relief in temperate and humid climatic conditions during the Interglacials. The letters, A, B, C, D, make reference to the morphological profiles (profiles on the bedrock = continuous lines; profiles on deposits = dashed lines) (from MAGALDI & SAURO, 1982).

The only difference between the two populations is represented by the lithology. In particular the large dolines of central Velebit are developed in a massive limestone breccia unit, that shows a very low sensitivity to cryoclastic weathering. During the last glaciation these dolines have acted as traps of wind transported snow, and have determined the formation of a plateau glacier, "radicated" inside the dolines and very thin outside these forms. In fact after the "Bora" wind had filled with snow the hollows, no more traps exist and so the snow was taken away from the flat surface of the plateau. In the southern Velebit the limestone is much more sensible to frost shattering and so most of the dolines have been partly dismantled by periglacial processes and partly filled by cryoclastic fragments and loess like deposits. On some slopes selective weathering has brought in relief the breccia filling some dolines, which is less sensitive to cryoclastic dismantling than the outside limestone.

Figure 5 *A partially filled doline and some completely filled "open dolines" with a flat horizontal floor not completely surrounded by slopes* (Monte Baldo).
The filling deposits are composed of rather angular limestone fragments embedded in yellowish silt.

So in these cases the main factor of the distinct landform evolution is represented by the different lithological characters of the limestone rock units.

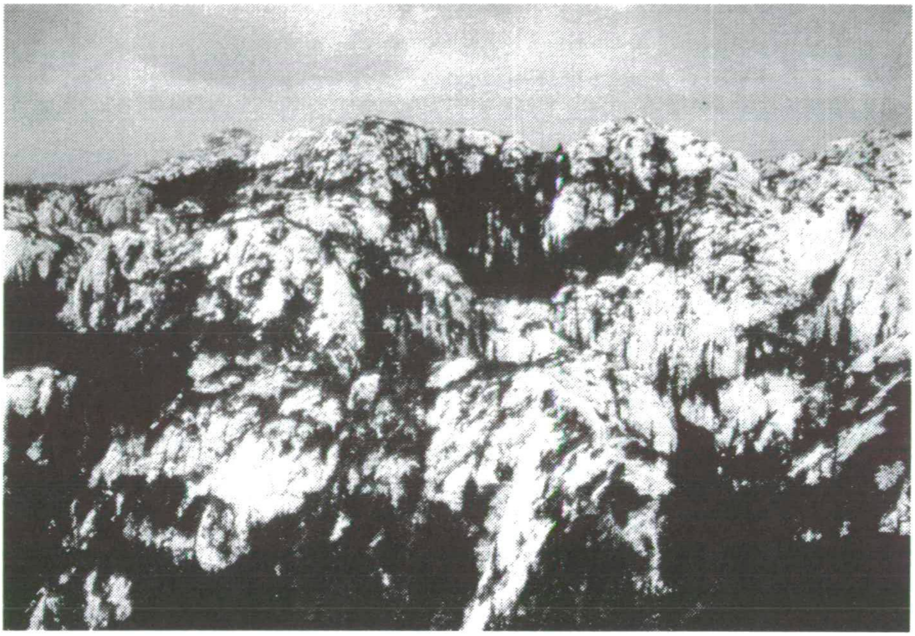


Figure 6 *The very large, deep, funnel shape dolines in the central Velebit (Hrvatska), developed in a massive limestone breccia unit that shows a very low sensitivity to cryoclastic weathering*. During the last glaciation these dolines have acted as traps of wind transported snow, and have determined the formation of a plateau glacier, "radicated" inside the dolines and very thin outside of these forms.

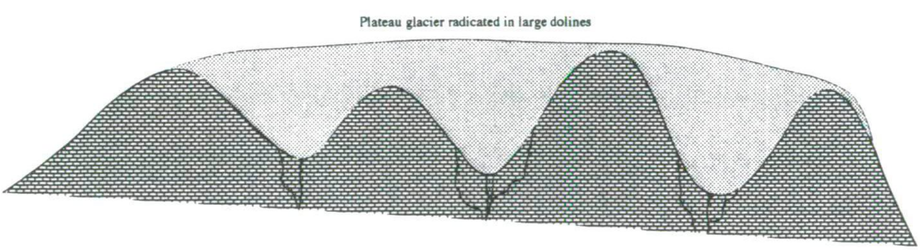


Figure 7 *Sketch profile of the plateau glacier radicated in the large dolines which should have existed during the last glaciation in the central Velebit plateau (Hrvatska).*

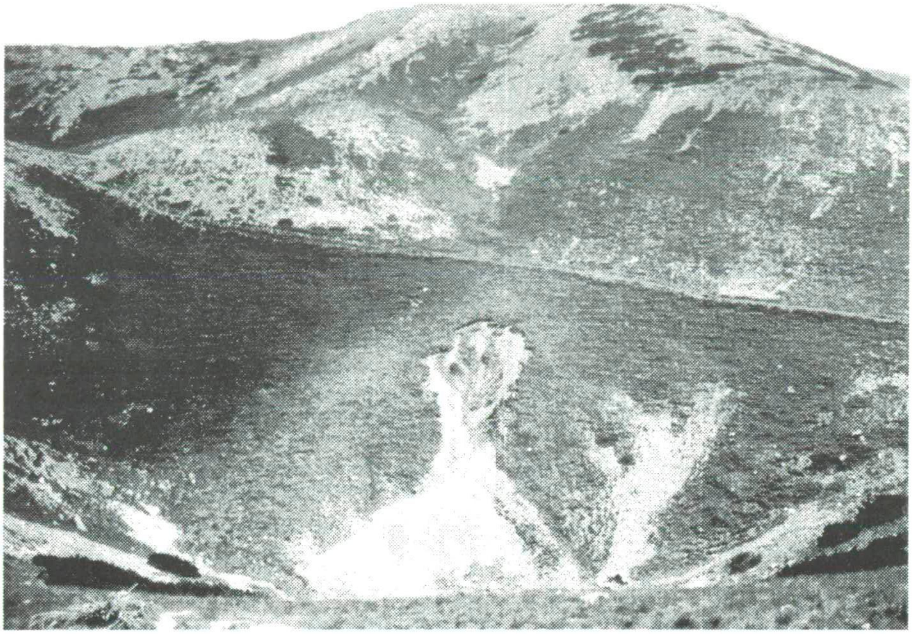


Figure 8 *Doline in the southern Velebit (Hrvatska), similar to those of M. Baldo. Inside the dolines a karstic consumption and absorption of the filling deposits in now occurring.*

An other interesting example is that of the "low relief cockpit karst" of Alte Murge (Puglia, Italy) where the karst hollows have been partially filled by volcanic ashes, in successive stages (SAURO, 1991). The filling deposits have favoured the development of an embryonic hydrographic network constituted by flat or rounded valley floors. In periglacial environment valley patterns have also developed on "inclined" plateau surfaces overlying a former doline relief.

SOME FINAL REMARKS ON DOLINE EVOLUTION

Dolines are not only topographical forms but also hydrological, lithological and sedimentological structures resulting from the presence inside the depressions, cut in soluble rocks, of fillings of different sediments with peculiar geometrical and sedimentological characters.

So if we want to understand the evolution of dolines we must consider:

- the lithological and tectonic control;
- the interrelations between karst and non karstic processes;
- the characters and influence of fillings.

In fact in doline evolution we assist to interchanges and mutations as:

1) from hydrological structures to cryptoforms;

2) from cryptoforms to epiforms;

3) shape and structure modifications by interference between karstic, slope, fluvial, periglacial and glacial processes.

The first stage of doline evolution is certainly explained by the role of the "epikarstic zone." In the sense of WILLIAMS (1985) the "epikarstic zone" is the upper part of the karstified rock volume, with a larger and more diffused secondary porosity by growth of karst voids.

Normally there is not a direct contact between the epikarst rock surface and the atmosphere, but a filter formed by the "loose covers," made by soil, soil sediments and a mixture of soil sediments, allogenic sediments (volcanic, eolian ...), insoluble residuals, and rocky fragments.

We will call this "filter body" "epicover.

"The "epicover" above the "epikarst" may be also interested by karstification when it contains rocky fragments or carbonate residuals.

The development of "cryptoforms" and the transformation from "cryptoforms" to "epiforms" may be explained by three main aspects:

- the character of "epicover" (three dimension geometry, permeability, water capability, percent and surface of soluble fragments, etc.);
- the processes at the "interface" between the "epicover" and the "epikarst";
- the characters and hydrological behaviour of the epikarst.

All these aspects are linked with the environmental processes of the outer surface and with the control of the topography, lithology and tectonic.

The three dimensions structures of the epicover are characterized by a net of wedges and, at the crossing of the meshes, by cones and cylinders.

Inside this structure an "epicover aquifer" exists, strictly interconnected with the "epikarstic aquifer. The two aquifers could be called "epiaquifers".

When in correspondence with a "cone" or a cryptodoline an epidoline develops, slope processes play a role inside the basin and mass transfer from the upper part of the form to the lower one occurs.

Carbonate soluble fragments, detached by weathering, are carried by slope processes from the sides of the doline to the bottom. Therefore, the weathering of the slopes causes an enlargement of the depression, a reduction of the steepness of the slopes, an abating of the depth and an increasing of the average diameter/depth ratio; beside this most of the rock surface, which may become in contact with the water solutions, is no more on the slopes but inside the filling deposits. So a large part of the solution capability is used inside this clastic, partly soluble body.

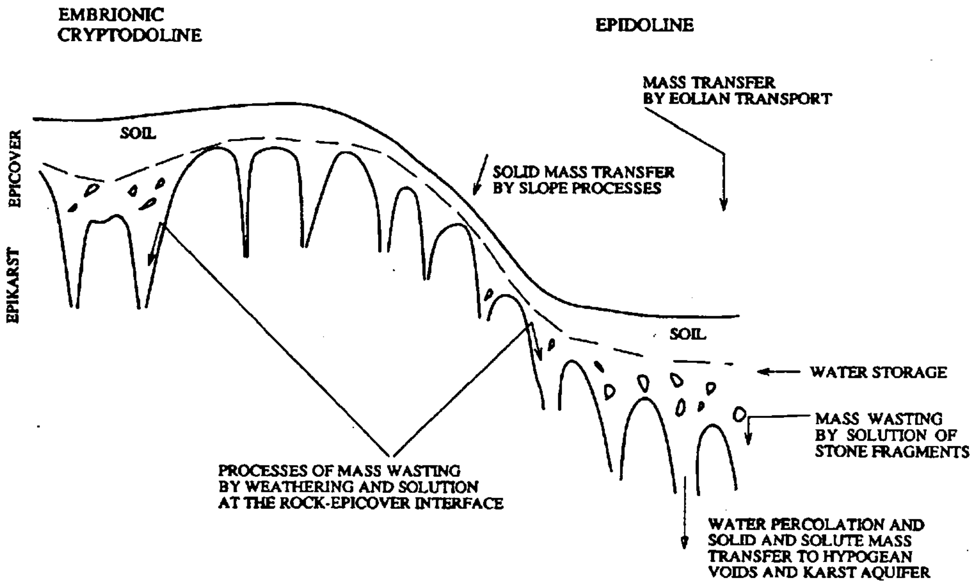


Figure 9 *Sketch profile of structures and processes occurring inside cryptodolines and epidolines.*

In the karst of middle latitudes, if the sensitivity to frost shattering of the soluble rocks is high, the bottom deposits may become very thick (also more than 10 m thick) and may preserve from the cryoclastic weathering the buried part of the slopes that may remain steeper than the upper exposed part.

A very important factor is also the mass trapping inside the basin of allogenic materials as loess, volcanic ashes, etc.

Examples of filling deposits of dolines in different karst areas of the world show how complex may be the history of these forms and how the deposits trapped inside the closed depressions may contain very important information about landscape evolution and environmental changes.

Further research work is necessary devoted not only to the surface forms but to the entire structure of dolines.

LITERATURE

AGNESI V., MACALUSO T., MENEGHEL M., SAURO U. (1989) - Geomorfologia dell'area carsica di S.Ninfa. In "I Gessi di Santa Ninfa", Memorie dell'Istituto Italiano di Speleologia, 3 (2), 23-48.

AUBERT D. (1966) - Structure, activitÄ et evolution d'une doline. Bulletin de la SocietÄ Neuchateloise des Sciences Naturelles, 89, 113-120.

BÁRÁNY-KEVEI I., MEZŐSI G. (1991) - Further morphometrical data from some important hungarian karst areas. Proceedings of the International Conference on Environmental Changes in Karst Areas, IGU-UIS, Quaderni del Dipartimento di Geografia, Universitê di Padova, 13, 137-142.

BONDESAN A., MENEGHEL M. & SAURO U. (1992) - Morphometric Analysis of Dolines. International Journal of Speleology, 21(1-4), 1-55.

CASTIGLIONI G.B. (1964) - Forme del carsismo superficiale sull'altopiano del Cansiglio. Atti Istituto Veneto di Scienze, Lettere ed Arti, 122, 327-344.

CASTIGLIONI G.B., CREMASCHI M., GUERRESCHI A., MENEGHEL M., SAURO U. & VAN VLIET LANOE B. (1990) - The Loess Deposits in the Lessini plateau. In "The loess in Northern and Central Italy", CREMASCHI M. Ed., 41-59.

CELI M. (1991) - The impact of bombs of World War I on limestone slopes of Monte Grappa. Proc. Intern. Conf. on Environmental Changes in Karst Areas - IGU-UIS, Quaderni del Dip. Geogr. Univ. Padova, 13, 279-287.

CUCCHI F. , FORTI F., ULCIGRAI F. (1975) - Relazioni tra tettonica e morfogenesi di doline del Carso Triestino e Monfalconese. Atti e Memorie della Commissione Grotte "E. Boegan", 15, 57-71.

DAY M.J. (1983) - Doline morphology and development in Barbados. Annals of Association of American Geographers, 73 (2), 206-219.

FORD D.C.(1964) - Origin of closed depressions in the central Mendip Hills. Proceeding of the 20th International Geographical Congress, Abstracts, 105-106.

FORD D., WILLIAMS P.W. (1989) - Karst geomorphology and hydrology. Unwin Hyman, London, 601 pp.

FORTI F. (1972) - Osservazioni geomorfologiche sulle doline del Carso Triestino. Atti 1lí Congresso Nazionale Speleologia , Genova, Nov. 1972, 239-243.

GAMS I. (1974) Kras. Ljubliana, izdala Slovenska matica.

HABIC P. (1990) - Cetvrti skup geomofologa Jugoslavije. Pirot, 20-23 June 1989, Geographical Faculty of Beograd, 55-60.

JAKUCS L. (1977) - Morphogenetics of karst regions. Variants of karst evolution. Akademiai Kiado, Budapest, 284 pp.

JENNINGS J.N. (1985) - Karst geomorphology. Blackwell, Oxford, 293 pp.

MAGALDI D., SAURO U. (1982) - Landforms and soil evolution in some karstic areas of the Lessini Mountains and Monte Baldo (Verona, Northern Italy). Geografia Fisica e Dinamica Quaternaria, 5 , 82-101.

NICOD J. (1975) - Corrosion de tipe crypto-karstique dans le karst mediterranien. Bull. Ass. Geogr. Fr. n. 428, 284-297.

PALMQUIST R.C. (1976) - Distribution and density of dolines in areas of mantled karst and hydrologic problems in karst regions. In DILAMARTER R.R., CSALLANY S.C.(eds.), Western Kentuky University Press, Bowling Green, Ky, 117-129.

PALMQUIST R.C. (1979) - Geologic controls on doline characteristics in mantled karst. Zeitschrift f/r Geomorphologie, Suppl. Band 32, 90-136.

PÉCSI M. (Ed.) Environmental and dynamic geomorphology. Akadémiai Kiadó, Budapest, 97-107.

SAURO U. (1973) - Il Paesaggio degli alti Lessini. Studio geomorfologico. Museo Civico Storia Naturale di Verona, Mem. f. s. 6, 161 pp.

SAURO U. (1974) - Aspetti dell'evoluzione carsica legata a particolari condizioni litologiche e tettoniche negli Alti Lessini. Bollettino Societê Geologica Italiana, 93, 945-969.

SAURO U. (1979) - Morfologia carsica. In CASTIGLIONI G.B., "Geomorfologia",UTET, Torino, 208-254.

SAURO U. (1991) - A Polygonal karst in Alte Murge (Puglia, Southern Italy). Zeitschrift für Geomorphologie, N.F. 35/2, 207-223.

SPERLING C. H.B. , GOUDIE A.S., STODDARD D.R., POOLE G.G. (1977) - Dolines of the Dorset Chalklands and other areas in Southern Britain. Transactions of the Institute of British Geographers, N.S., 2, 205-223.

SWEETING M.M. (1972) - Karst landforms. Macmillan, London, 362 pp.

TROESTER J.W. WHITE E.L. WHITE W.B. (1984) - A comparison of sinkhole depth frequency distributions in temperate and tropical karst regions. In BECK B.F. (ed.), "Sinkholes: their geology, engineering and environmental impact", 65-73, Balkema, Rotterdam.

WHITE W.B. (1988) - Geomorphology and Hydrology of carbonate terrains. University Press, Oxford, 464 pp.

WILLIAMS P.W. (1971) - Illustrating morphometric analysis of karst with examples from New Guinea. Zeitschrift für Geomorphologie, 15, 40-61.

WILLIAMS P.W. (1985) - Subcutaneous hydrology and the development of doline and cockpit karst. Zeitschrift f/r Geomorphologie, 29, 463-482.

ZAMBO L. (1985) - Investigation of karst infiltration in mountainous areas covered with red clay. Geographical papers 6, Zagreb, 85-92.

ZAMBO L. (1985) - The role of clay deposits in the geomorphic evolution of dolines. in

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REGIONALITY OF KARST AND THE HUMAN ACTIVITY IN GUNUNG SEWU, JAVA ISLAND

URUSHIBARA-YOSHINO Kazuko

ABSTRACT

In Gunung Sewu, Java Island, there exist 4 marine terraces and hill areas with cone karst. Areas having high cones show a high cone density which is in contrast to areas on the younger terraces in which there are only small cones.

In Miocene marly limestone areas (Wonosari polje), the population density was 936/km^2 in 1991. But in the typical cone karst areas of pure Miocene limestones the density is quite low (277-359/km^2) due to the poor condition for agriculture land use.

During strong El Nino years like 1982-83, when Java Island suffered from drought, the population and number of families in the cone karst areas decreased intensively. On the other hand, in marly limestone areas, the population and number of families have been not so greatly affected by the drought caused by El Nino. Because of the relatively high productivity in this area and the progressed urbanization, such as in Wonosari, people from the surrounding low productivity areas of cone karst flowed to these region.

INTRODUCTION

In the humid tropical area, solution of limestone occurs effectively. When the limestone area is covered by vegetation and heavy clay, solution ratio of limestone is extremely high under the condition of high precipitation during long rainy season. Lithological and tectonical conditions, acidity of soils, CO_2 contents in soil, the properties of litter and topography relate to karstification very much. In the humid tropical areas, the connection of these factors can form cone karst.

The cone karst develops independently to the of geological ages of limestone. We can observe such a phenomenon in the Tertiary limestone areas in some countries in Southeast Asia and Central America. Furthermore, Verstappen (1960) reported cone karst in the Quaternary uplifted coral areas in Malaysia.

In the Gunung Sewu in Java Island, where the present study is carrying on, cone karst develops well in the Tertiary limestone areas. Cones and cockpits are distributed in the areas along the geotectonical lines and lineaments of limestone (Waltham et al., 1983, 85). In these areas, the human activities have been very strong, since the stone age. Nowadays, density of population in these areas have been kept very high, even peoples have problems to find enough water for agriculture and living. In order to clarify, the relationship between the precipitation fluctuation and population change, was examined by a study in the Gunung Sewu in Java Island.

TOPOGRAPHY AND CLIMATE IN GUNUNG SEWU

In Gunung Sewu, the cone karst was studied by LEHMANN (1936), BALÁZS (1968), VERSTAPPEN (1977) and WALTHAM et al. (1983,85). They reported cave systems and underground systems. Miocene limestone distributes along the Indian ocean. *Fig. 1.* shows the volcanic areas in central Java and the limestone areas. Gunung Sewu, which means thousand mountains, locates in 50-150 km southeast from Yogyakarta. The number of cones is estimated as about 40000 in an area of 1300 km^2. The Gunung Sewu area has been uplifted might accelerate more solution. These area might be uplifted actively during the Quaternary period, which several marine terraces with well developed clearly demonstrate. Around the mouth of Kladen river, shown on *Fig. 2.*, 4 marine terraces developed very well along the coast in the limestone areas and in the sandstone areas, which are covered by layers of limestone. Big cones developed very well, particularly on the higher terraces composed of limestone.

On the lowest terraces (15-20 m a.s.l.), the cones are very small in size. In contrast, on the oldest terraces (80 m a.s.l.), deep dolines and high, big sized cones developed. As we can see on *Fig. 2*, the distribution pattern of cones seems to be controlled strongly by tectonical lines as lineaments and fault lines. People use deep dolines like Telaga as reservoirs. Especially in the mountain areas, density of Telaga increases.

In the Gunung Sewu, which is located at about 8°S, rainy season occurs from November to March under the influence of westerly winds. On the other hand, dry season is from May to October under the influence of easterly winds. But the fluctuation in length of rainy season and precipitation amounts are very large. EGUCHI (1988) reported that rainfall controlled by westerly from the Indian-ocean instead of under the ITCZ. But position of ITCZ is a distribution boundary of rainfall and clouds. Therefore, it should be pointed out that Java Island is a very sensitive area for rainfall

HUMAN ACTIVITY AND MICRO-TOPOGRAPHY OF KARST

(1) Micro-topography and agriculture

In Gunung Sewu, population density is extremely high. Since the areas have been used for agriculture, there exist no original or secondary forests. The cones covered shallow soils are using for terraced farm lands, if cones are lower than about 50 m. When the cones are too much high or large for making farm land, they are afforested with teak and acacia. *Photo. 1* shows the land use of cone karst. Main agricultural lands are located in the bottom of dolines, cockpits and at the bottom of dry valleys. *Fig. 3* shows the farm lands in the bottom of dolines and dry valley near Sadeng. The boundary of rice fields are

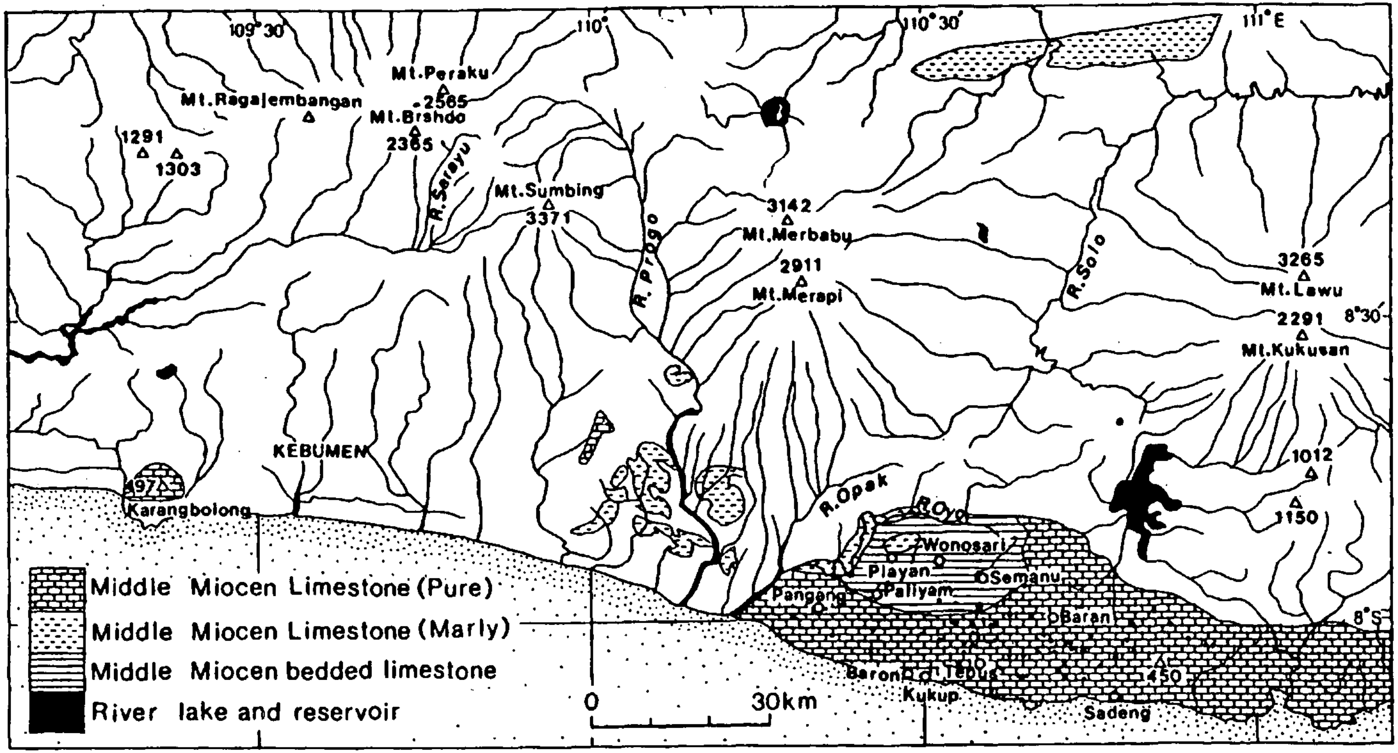

Figure 1 *Distribution map of Miocene limestone and calcareous marl, Tertiary in Southeastern part of Java Island*

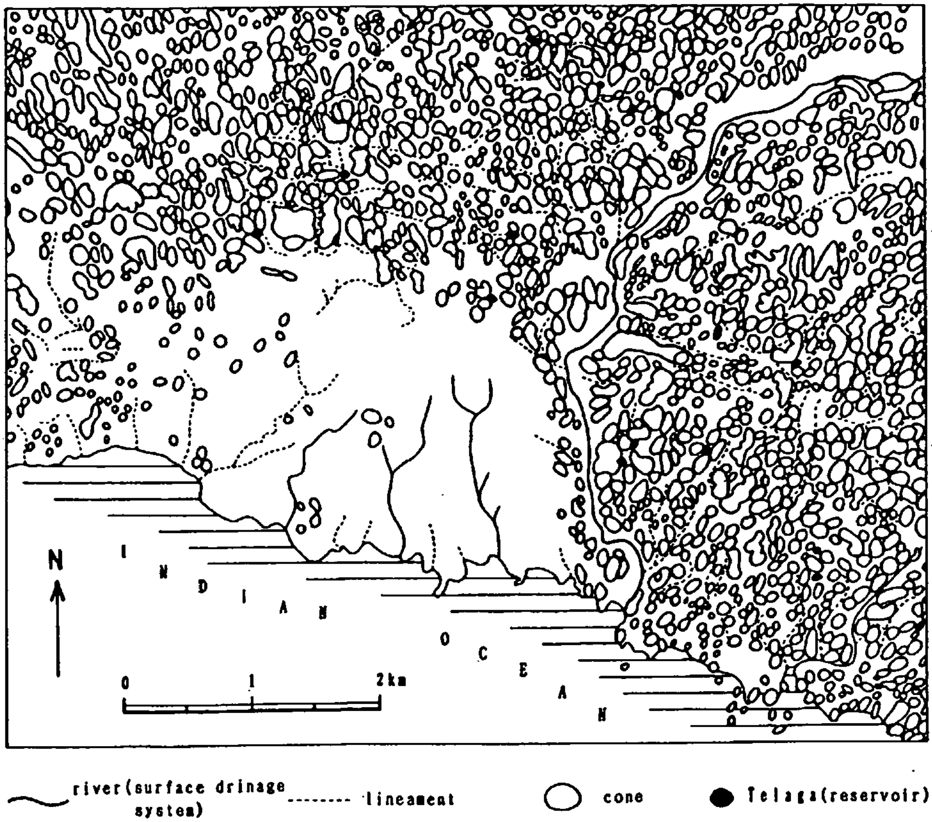

Figure 2 *Topography and drainage systems in limestone and sandstone areas at the river mouth of Kladen river*

controlled by the condition of micro-topography. The farm lands in the bottom of doline or depression areas are used as fields. But the slopes of cones are used only for poor fields during all seasons. The deep soil filled depression, which have springs, are used as Telaga. The model of land use by season are shown on *Fig. 4* (Urushiba-Yoshino, 1991). In the most poor areas for cultivation, only cassava is seen.

(2) Population density and soils

In part of the inland area of Gunung Sewu, geology is composed by Tertiary Miocene marl. This area is a karst polje with Grumusol, which is very fertile for agriculture, because of containing montmorillonite. Areas outside of limestone are composed by andesite or sandstone.

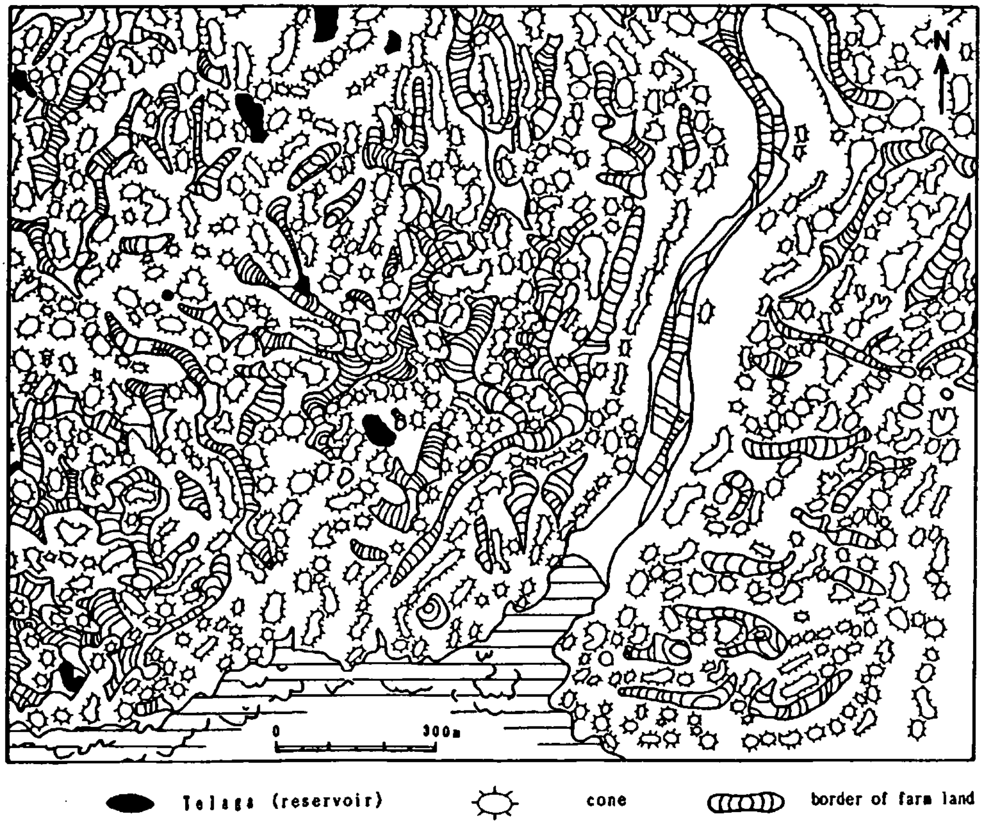

Figure 3 *The border of farm land controlled by micro-topography in cone karst and Sadeng dry valley*

These areas are covered by thick Latosol. The distribution map of soils is shown on *Fig. 5*. The population density of subdistricts is related to soil type. Especially, it is noteworthy that Wonosari subdistrict having Grumusol keeps 936/km^2 (1991). This population density is almost equal to the paddy cultivation area in a rich alluvial plain. The pure limestone are Paliyan, Rongkop and Tepus. The population of Tepus 359/km^2 has the highest value. It seems to be that the cone karst areas have reached their limit of population density. Latosol areas in other geological conditions can keep higher densities than in the Red soil areas in one karst area.

(3) Population in karst areas

It is well known that El Nino is one of the causes of abnormal climate in the Monsoon area. Especially strong El Nino 1982-83, weak one 1987 and weak one 1991-93 are well known.

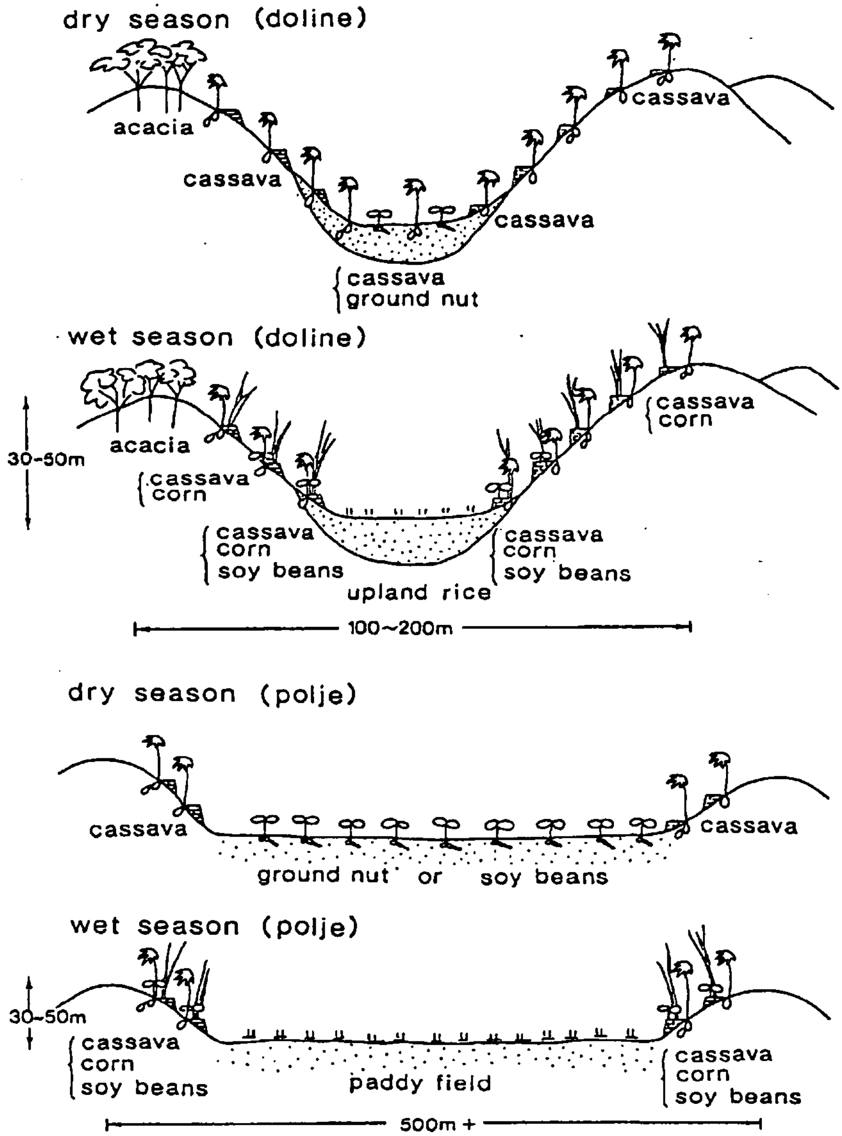

Figure 4 *Agricultural crops in the dry season and wet season in the polje and doline in Gunung Sewu*

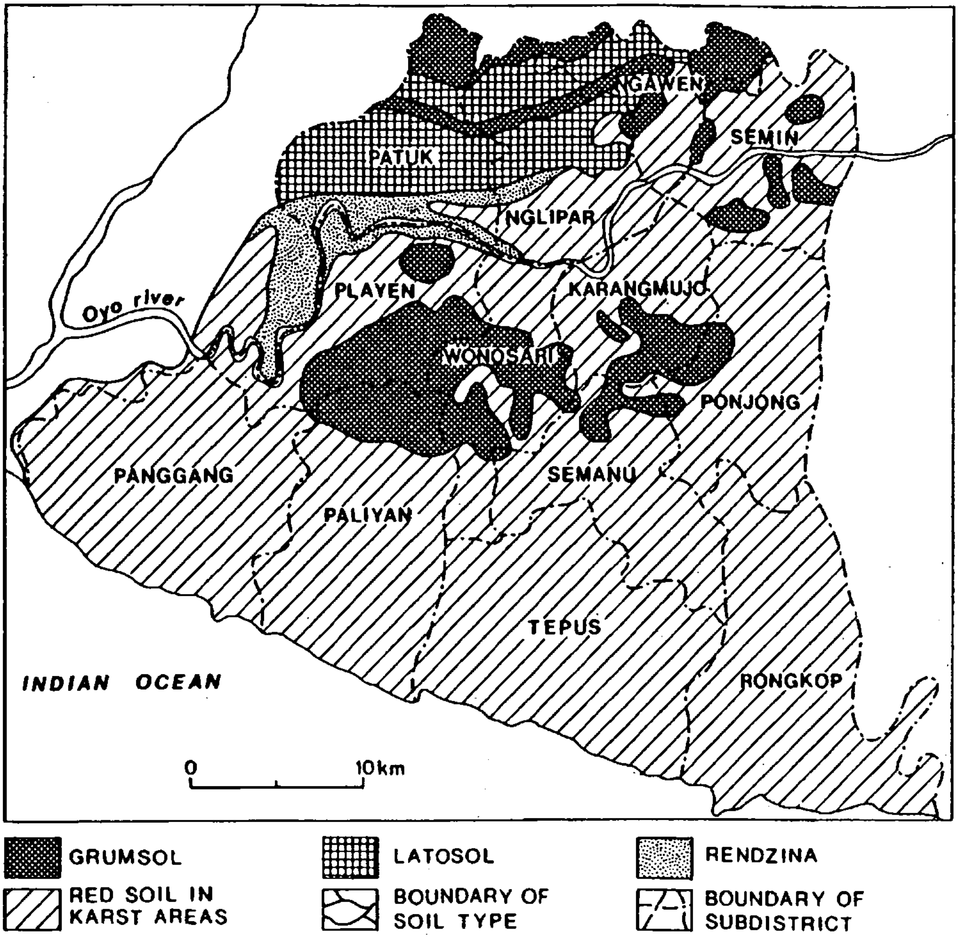

Figure 5 *Soil distribution and the subdistrict of Gunung Kidul*

The relation between El Nino and precipitation in Java Island is shown on *Fig. 6*. The precipitation from 1980 to 1991 and the anomaly of sea surface temperature at 120° W show clearly the effect of El Nino which caused particular as long dry season without rainfall in 1982 and less rainfall in the wet season of 1982/83.

In 1987 El Nino year, it appeared that the dry season of 1987 was longer than in a normal year. Since 1980, the population and family number of subdistricts we got from the Statistical Office in Yogyakarta. *Fig. 7* shows the comparison of population and families in the red soil areas (Panggang, Rongkop) and Grumusol areas (Wonosari). Population and family numbers of 1983 decreased in Pangang and Rongkop dramatically. In 1987, the population in Panggang and Rongkop decreased. But, in both El Nino years, population

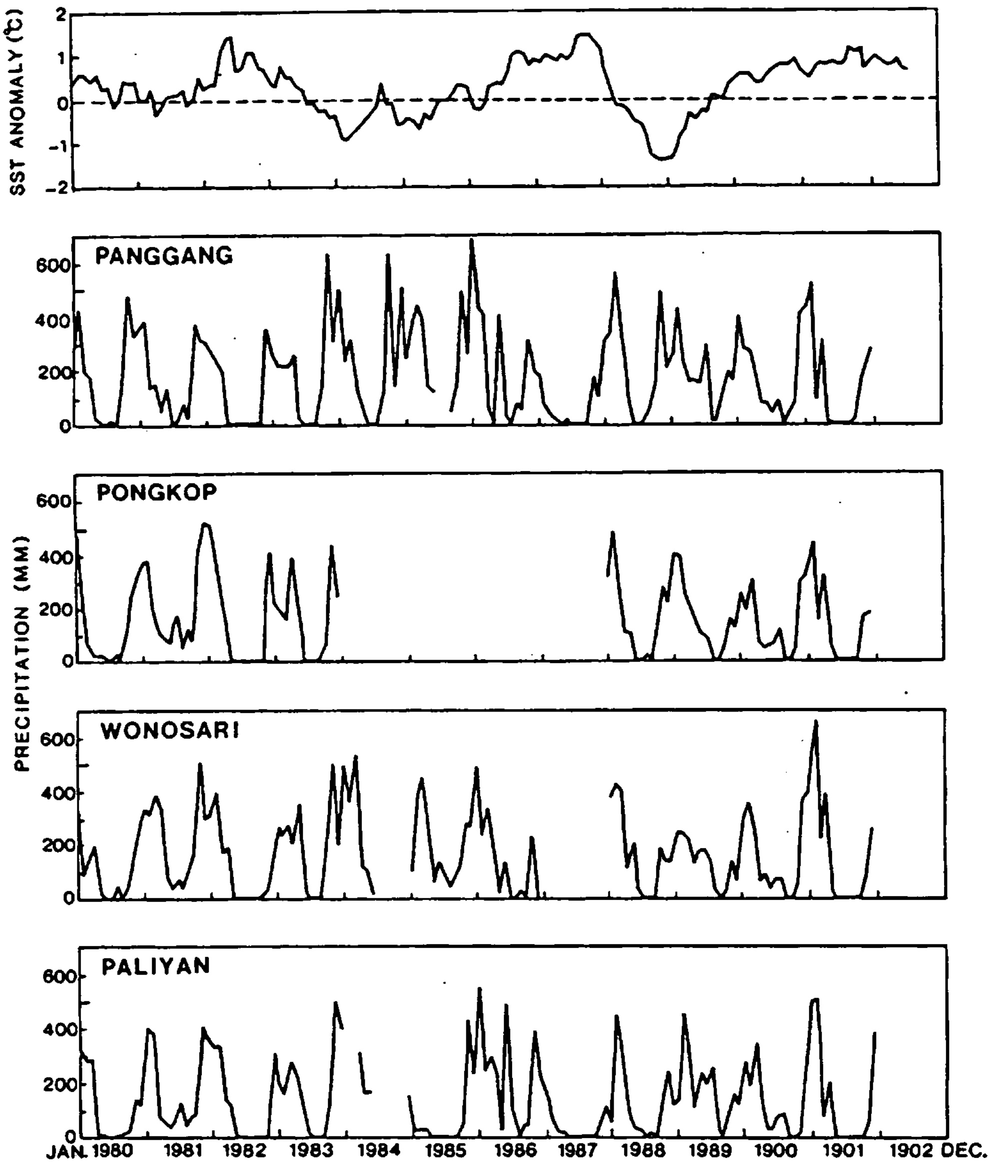

Figure 6 *Fluctuation of SST annomaly in the sea area os El Nino 4 and precipitation at 4 stations in Gunung Kidul 1980-1991*

and family number is steadily increased in Wonosari. It seems the Wonosari was not so strongly effected by El Nino, and people moved from the cone karst areas to Wonosari or some other city urban areas under such anomalous weather conditions.

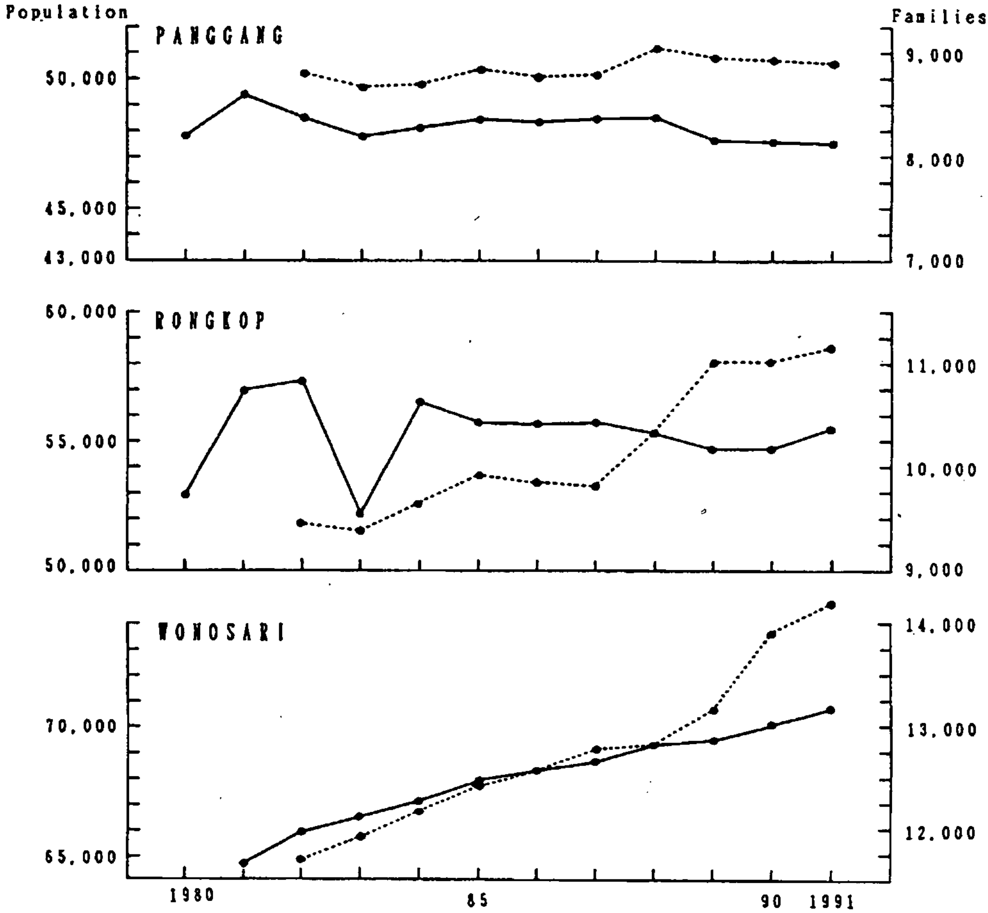

Figure 7 *Changes of population and number of families in Panggang, Rongkop, Wonosari in 1980-1991. Full lines show population and dotted line the number of families*

In 1983, they were sensitive for drought in cone karst area. Especially the polje areas of Grumusol and Red soils in limestone area with cone karst were affected seriously by anomalous weather conditions caused by El Nino. Some traditional Telaga were also dried up in the drought year in cone karst areas. So the government tried to find a way to supply constant water quantities for agriculture and living.

Since 1980's, the Government supported the building of tanks which collect rainfall through roves of houses. After that, the Government tried to pump up underground water with one set for each 5 families (*Photo 2*). Since 1991, each of the families must pay for water supply by the measured amount used. This means that the farmers had to change the

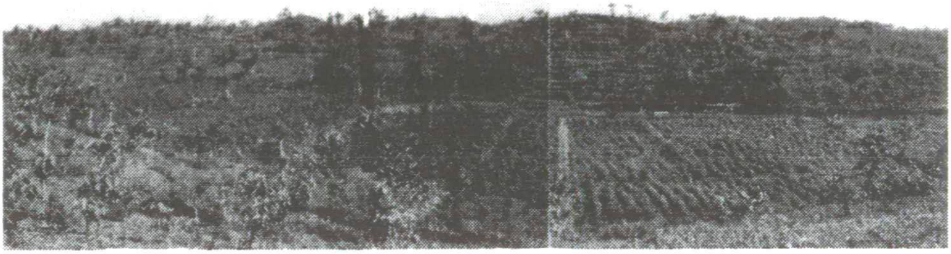

Photo 1 *Agricultural land use in the cone karst areas of Gunung Kidul and within the dolines (taken by URUSHIBA-YOSHINO on 04. Jan. 1994)*

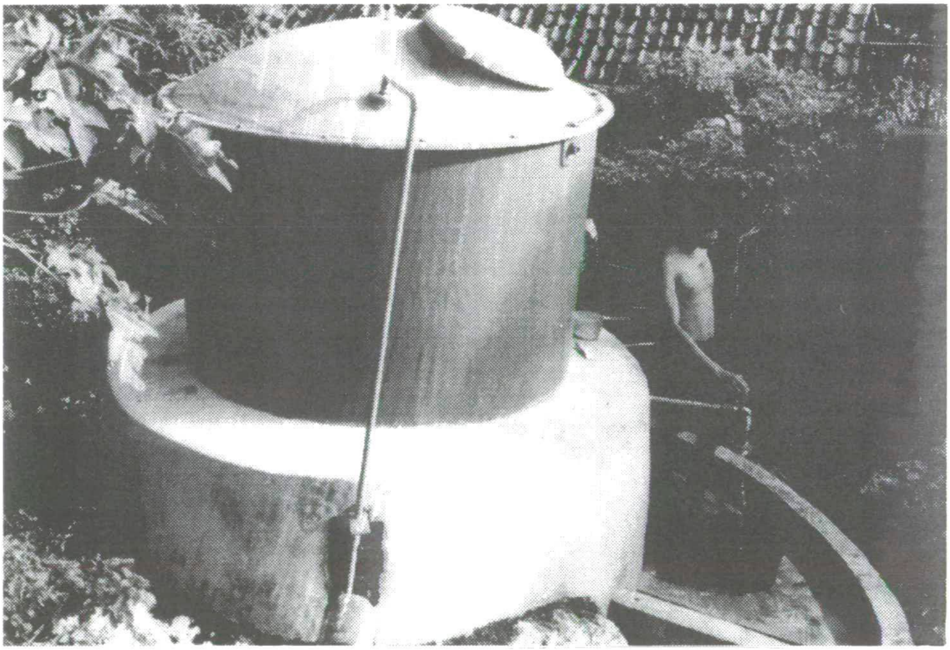

Photo 2 *A tank for water supply which is supplied since 1991 for 5 families each (taken by URUSHIBA-YOSHINO on 04. Jan. 1994)*

system of cost-free water to charged water. For the farmers, the water supply is a heavy economic burden. These areas are still restricted at present, but the water problem will become a more severe in the near future.

CONCLUSIONS

1, In cone karst areas, the population density is usually very low in the other countries like as Puerto Rico and Jamaica. But in Gunung Sewu, the population density is exceptionally high being about 395/km² (Tepus, 1991). therefore, agricultural land use is very intensive. On the other hand, the Grumusol area in a Polje has high productivities, but population density is also high, 936/km² (Wonosari, 1991).

2, During the El Nino years like 1982-83, population and family numbers decreased in the especially most dense cone karst of Panggang and Rongkop. But, in Wonosari, population and family numbers increased continuously showing no relation to El Nino years.

3, In weak El Nino year of 1987, Panggang and Rongkop had very abnormal weather conditions. El Nino caused a slight decrease of population and family numbers.

4, It is obvious that the drought caused by El Nino resulted in an out-flow of farmers from limestone areas to the productive areas such as Wonosari.

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REFERENCES

BALÁZS, D. (1968): "Karst region in Indonesia". p. 61.

EGUCHI, T. (1983): Rainfall distribution and air streams over Indonesia. Geograp. Review of Japan, 56(3), p. 151-170.

LEHMANN, H. (1936): Morpologische Studien auf Java. Geogr. Abhandl.,9, p. 15-67.

SARTONO, S. (1976): Genesis of the solo terraces. Mod. Quaternary Res. SE Asia, 2, p. 1-21.

SWEETING, M.M. (1972): Karst landforms. Macmillan, p. 362.

SWEETING, M.M. (1992): Tectonics and fluvial denudation in the formation of cone karst, with particular reference to South China. Tübinger Geographishe Studien, Tübingen, 109, 45-56.

UHLIG, H. (1980): Man and tropical karst in Southeast Asia. GeoJournal, 4(1), p. 31-44.

URUSHIBARA-YOSHINO, K. (1991): Land use and soils in karst areas of Java, Indonesia. Proceedings of the International Conference on Environmental Changes in Karst Areas, Quaderni del Dipertimento di Geografia, Universita di Padova, p. 61-67.

URUSHIBARA-YOSHINO, K. (1992): Reconstruct of Palaeo environment based on soil and vegetation in Tropical Asia. "Preliminary study on Palaeo environment of Tropical Monsoon Asia". Research Center for Regional Geography, Hiroshima University, (22), p. 60-70.

URUSHIBARA-YOSHINO, K. (1993): Human impact on karst soils Japanese and other examples. Catena, Supplement, (25), Cleinlingen, p. 219-233.

VERSTAPPEN, H.Th. (1960): Some observation on karst development in Malaya Archipelago. Jour. Trop. Geography, 14, p. 1-10.

VERSTAPPEN, H.Th. (1969): The state of karst research in Indonesia. In:Verstapppen, H.Th., "Problems of the karst denudation", Brno Czechoslovakia, p. 139-148.

VERSTAPPEN, H.Th. (1977): The use of aerial photographs in geomorphological mapping. In:ITC Textbook of Photo-Interpretation, &, Inter. Inst. for Aerial Survey and Earth Sciences.

WALTHAM, A.C.-SMART, P.L.-EAVIS, A.J.-ATKINSON, T.C. (1983): The caves of Gunung Sewu, Java. Cave Science, Trans. British Cave Research Association, 10 (2), p. 55-96.

WALTHAM, A.C.-SMART, P.L.-EAVIS, A.J.-ATKINSON, T.C. (1985): Exploration of caves for rural water supplies in the Gunung Sewu karst, Java. Annales du la Societe Geologique de Belgique, 10, p. 27-31.

WILLIAMS, P.W. (1971): Illustrating morphometric analysis of karst with example from New Guinea. Zeitschrift für Geomorphologie, 15 (1), 40-61.

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ECOLOGICAL CHARACTERISTICS OF DOLINE TYPES IN AGGTELEK HILLS (NORTH HUNGARY)

Ilona Bárány - Gábor Mezősi

INTRODUCTION

In recent years, a number of proposals have been put forward to typify the repeatedly buried and exhumed surfaces of the Hungarian Mountains and distinguish their geomorphological surfaces (PÉCSI,M. 1984; PÉCSI,M. and MEZŐSI,G. 1985, etc.). This paper presents a survey of our karst morphological investigations in the Aggtelek Mountains, with a view to clarifying the disputed questions of surface development in Late Quaternary. We assume that conclusions can be drawn for the date of the final exhumation of the individual morphogenetic units from the complex system of forms that developed on their surfaces. The central feature of our studies was the karstic depressions in various lithologic, tectonic and orographic situations. Our analyses permitted the identification of the doline types belonging to the most important morphogenetic units and an estimation of their ecological state.

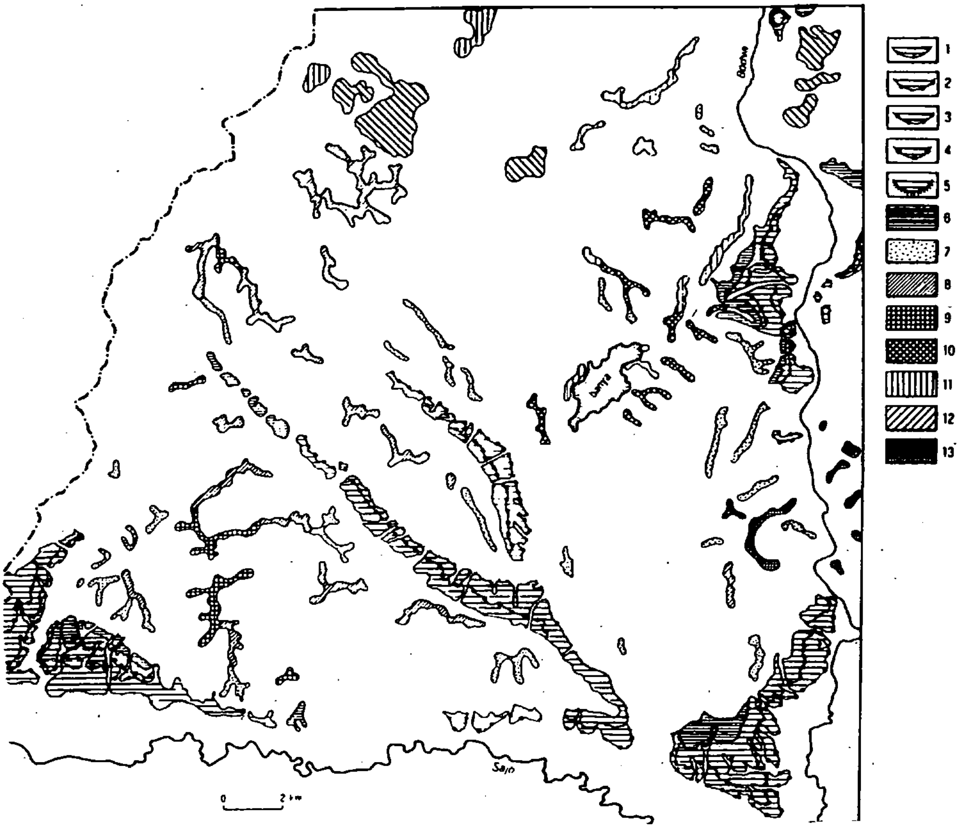
RESULTS

Geomorphological surfaces of the mesozoic horsts of the N-Hungarian Mountains

From a structural-morphological aspect, the Rudabánya-Aggtelek Mountains comprise a folded-faulted (some authors consider it to be covered) horst planated in the Mesozoic. The paleokarstic erosional surface was repeatedly buried and exhumed during the Tertiary (*Fig. 1*). In response to the Tertiary tectonic movements, it was dismembered into blocks undergoing independent development and eroding to various degrees. Because of their different geomorphic evolutions and positions, these mountains represent a relief subtype different from the previous ones. Orographically, they are now low mountains. The course of their general evolution may be summarized as follows:

The early Mesozoic areas of syncline type were transformed into mainland from the Upper Triassic, and up to the Middle Cretaceous planation prevailed under tropical subhumid climatic conditions. At the end of Mesozoic the low, "karstic", tropical erosional surface was dismembered by major faults. Although the climatic conditions would have permitted a further period of (regional) planation, extending to the entire Hungarian Mountains, active tectonism turned this region into a pediment zone of the higher, crystalline mountains to the north and south.

Geomorphologically, therefore, it may be assumed that peneplanation was followed by pediplanation in the Eocene.



1 - terrace II/a; 2 - terrace II/b; 3 - terrace III, travertine horizon; 4 - terrace IV, travertine horizon; 5 - terrace V; 6 - Upper Pliocene pediment (locally red clay formation); 7 lower interfluvial ridges, derasional terrace steps, remnants of older pediment surfaces; 8 - higher hill-summit surfaces, or interfluvial ridges (initial phases of Quaternary valley formation); 9 - Neogene pediplain remnants; 10 - semiexhumed planated horst surface transformed by pedimentation (covered by Paleogene sediments); 11 - moderately elevated planated horst surfaces (exhumed in Tertiary and Quaternary); 12 - bare planated horst surface in summit position, completely exhumed and intensely karstified; 13 - repeatedly buried and exhumed peneplain remnants built up from Paleozoic sediments; 14 - mine area

Figure 1 *Main geomorphological levels in the Aggtelek-Rudabánya Mountains and their environment*

Subsequently, during the Paleogene and particularly the Neogene, the surface was covered by sediments of varying thicknesses and kinds.As a result of these tectonic movements, which lasted from the end of the Miocene up to the Pleistocene and affected only certain zones, and also as a result of the oncoming erosional activity, this region was transformed into partially or completely exhumed low mountains with a horstgraben structure. Accordingly, the true horst surfaces lost their young Tertiary sediment mantles and underwent mountain margin pedimentation at the end of the Pliocene.

The investigations by LÁNG, S. (1973) and JAKUCS, L. (1964) indicated that neither the climatic nor the karst-hydrological conditions (the latter because of the hiqh karst-water table) of the formerly assumed Pliocene karstic planation were present.

By taking into consideration the orography and the differences in evolution too, we distinguished the following horst types (sometimes in combination).

(a) Exhumed planated horsts in summit position: including the completely exhumed plateaux of the Aggtelek and Martony Mountains, which underwent intensive karstification during the Quarternary.

(b) Moderately elevated planated horsts: the central part of the Rudabánya Mountains (preserved with ore indications), from which the original Paleogene cover was totally degraded during the Late Tertiary and the Quaternary.

(c) Semi-exhumed planated horst transformed by pedimentation: these elevated horsts are covered by spots of Oligocene or Miocene sediments of various depths (e.g. the margin of the Rudabánya Mountains).

These relief subtypes frequently differ in orographic position, but this does not mean morphogenetic variation (i.e. a higher position does not necessarily mean an older geomorphological surface). Accordingly, it would have been a mistake to identify the horst levels with geomorphological surfaces merely on the basis of their present position.

Doline types of Aggtelek Hills

The process of karst formation, which can be measured in geological periods, took place in the karst of Aggtelek Hills without being overlapped by non-karstic rock, thus typical karstic phenomena and varying karstic surface forms could take shape in this area. Accordingly, recent karst formation processes can be primarily studied on the latter karsts. We can find **solution dolines** here, which we consider to be characteristic forms of temperate zone karsts. Solution dolines occur as unique dolines, especially on the surface of karst plateaus. The appearance of row dolines is quite frequent in the valleys inherited from the planted karsts which are dry today.

Besides dolines, bare karr surface occurs less rarely, for example, the karr field on the shore of the lake in Aggtelek, whose rounded-off surface coloured by root-arms obviously refers to subterranean corrosion processes.

The formation and the development of solution dolines are influenced by several exogenic ecological factors. According to our concept, the climate and the microclimate play the most important part among them, with which the soil covering the rock the biological processes taking place in the soil and the vegetation settling on it will be developing in close interaction, and the dynamics of the subterranean corrosion denudation develop in connection with them. Besides the emphasis on the determining role of the climate, the soil and the biogenic factors, karst formation is not independent of the relief and neither of the structural and microtectonic endowments of the rock-bed and the forms largely show the period of the influence of the processes, too.

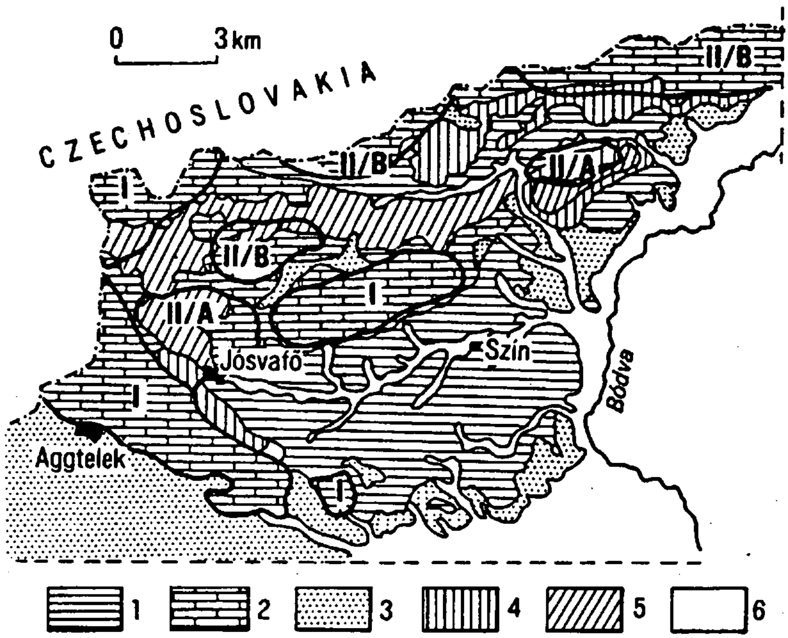
In accordance with the individual relief subtypes, we carried out detailed morphometric and litholoqical studies of the karstic depressions and their fills *(Fig. 2., Table 1)*. These revealed unambiguous correlations with the evolution of the zones of the depressions. On this basis, three main groups may be distinguished:

	Valley type	Basin type	Plateau type
relief ratio	0.08	0.14	0.12
elongation ratio	2.24	1.58	1.12
deep (m)	16.6	15.8	9
diameter (m)	207	113	75
average area of dolines/km²	0.01	0.02	0.016
total area of dolines as percentage of karst surface	23	32	31
doline density	11-13	32-36	7-9

Table 1 *Some morphometrical parameter of the different doline types in the Aggtelek region*

I. Dolines situated at a height of 310-350 m, with a diameter of 50-200 m and a depth of 15-40 m. Several large dolines frequently coalesced. Even disregarding the dolines, the terrain is strongly dismembered, with flat ridges of considerable extent where there are no, or only very few dolines, the peaks of these ridges even rise above 400 m. Most of the dolines are situated in rows and display N-S and W-E strikes. A typical fill is dark red terra rossa with a high iron oxide content (up to 14 %). This attains a layer thickness of 5-15 m on the doline bottoms. The doline sides and bottoms protected by the terra rossa exhibit definite tropical tower (?) karst microforms. Such forms are absent from the ridges and doline sides not covered by terra rossa, probably as a result of secondary, normal surface karst denudation processes shaping the relief. In the doline bottoms covered by red clay, the usual karren microforms are missing.

II.a. Dolines situated at a height of 270-280 m, with a diameter of 5-30 m and a depth generally not more than 2-8 m. The karstic terrain, rich in small dolines, has a fairly uniform height and a definite planation character. The material filling the depressions is yellowish-brown, and is primarily reminiscent of terra fusca, with a little terra rossa. The clay fill is 2-5 m thick, and is present not only on doline floors, but also on the ridges. The karstic limestone protrudes onto the surface at only a few sites, forming bare patches. The subsoil rock forms are primarily characterized by corrosional karren with the presence of fissure-karren.



1 - Lower Triassic (Campilian) limestone, shale; 2 - Lower Triassic (Gutenstein) limestone and dolomite; 3 - Wetterstein limestone; 4 - Wetterstein dolomite; 5 - Pliocene gravel, sandy gravel; 6 - extensive fluviatile sediment from Holocene; I - exhumed, intensely karstified karst; mainly "valley" type dolines; II/a - moderately elevated, weakly karstified, planated surface; mainly "basin" type doline; II/b - bare planated exhumed horst surface in summit position mainly "plateau" type doline

Figure 2 *Karst doline types in Aggtelek Mountains*

II.b. Dolines situated at a height of around 500 m and higher, with a diameter of 50-200 m and a depth of 20-50 m. These dolines generally have steeper sides than the dolines at intermediate heights; this may well be connected with the fact that they contain little fill which favours the expression of the morphology of the original rock surface. The terra rossa is almost completely missing; the fill is rather black humus, rendzina forest soil. We have not yet encountered with justified tropical tower karst forms; both on the surface and under the generally thin soil layer, the microforms merely display the features of root and precipitation corrosion and of cryofraction. As far as their positions are concerned, the dolines are not aligned in definite rows; the terrain is a uniplanar plateau, generally presenting a picture only of a karstic erosional surface.

The relative ages of the various horsts as geomorphological surfaces can be given on the basis of the related doline types, in the following manner:

By the end of the Pannonian (Late Miocene), the surface had progressively lost its pediment position. Of the surface segments along the earlier tectonic lines, II/b was exhumed first, followed by II/a (currently in a basin position). In our view, the exhumation of unit I can be regarded complete: the remnants of the Pannonian gravel mantle are to be found in a number of sites. At the same time, the karstic valleys that appeared on its surface in the Pleistocene have exposed the older karstic form complex, additionally including dolina row formation, which meant the starting phase of intense karstification. Here, therefore, "old" and "young" karstic forms are found side by side in the same orographic situation.

Microclimatological characteristics of the dolina types

As we have mentioned it above, the determining exogenic factor in the development of dolines is the climate, which roughly defines the effect-mechanism of the ecological factors. The dolines modify the radiation effects within the local climate of the mountain and the valley respectively, thus creating an independent microclimatic system. The different slopes further dissect the microclimate of the doline within the microclimatic area resulted from the closedness of the karst depression.

The air-space of dolines is filled up by a cold airlake at night and by the high-temperature air by day stuck in the depression. In the heat-absorption and emission processes of the slopes, temporal difference and a difference of order are shown in compliance with the changes in the irradiation conditions. The shadow effect also plays an important part in the heat economy of dolines as a result of horizon limitedness. The symmetry axis of the air temperature in the North-South segment shifts in the direction of the slope facing South. The minimum temperatures shift in the direction of the slopes at night in case of fog (*Fig. 3*).

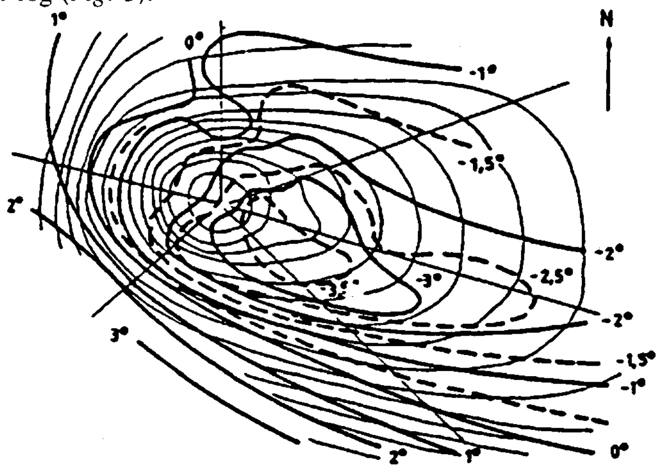


Figure 3 *Isotherms in a doline in Aggtelek Hills at night (17. 8. 1992)*

The soil temperature, which is important from the viewpoint of the processes in the soil, alters according to the changes of air temperature but with considerable phase-shift. The course of the sun influences the alternation of soil temperature, too. The soil layer close to the surface is the warmest on the North-Western slope by day (southern exposition), while the deeper layers of the soil are the warmest on the northern slope. The southern slope is the coldest (northern exposition) the biggest phase-shift can be experienced here moving toward the deeper layers. The expositional differences of soil temperature is considerable until the depth of 20 centimetres. This is significant as the biological processes of the soil take place here most intensively.

The expositional differences make it possible that the snow cover in winter remains for different periods; on the southern slope (northern exposition), the snow cover remains for a longer period because of the early occurrence of self-shadow and the low efficiency level of radiation arriving at a low angle, and the corrosion is faster under it than in places where snow does not remain for a long time. Consequently, the amplitudes of soil temperature are significantly smaller in the southern parts than in the northern ones.

Most important characteristics of doline-soils

In the Aggtelek Mountains, remnants of Mediterranean red soil (terra rossa), reddish brown soil, rendzina and brown forest soil are alternating in the dolines.The thickness of the soil on the slopes is of several 10 centimetres, while at the bottom of the dolines it can be of several meters even. The doline soils are usually strongly bound, they have high humus content (crude humus usually), their pH is weakly acidic or neutral. The pH has been showing some changes on the Aggtelek karst primarily (BÁRÁNY, I. 1987), which we demonstrated by means of the differences between the pH figures (in aqueous and potassium-chlorided solution). Presumably, the acidic depositions as well as the herding live-stock farming have contributed to forming the unfavourable tendency. In lower strata of the doline soils, a level of Fe accumulation can be detected, which is the result of matter transcumulation. The doline soils are deficient in ionic constituents just at the bottom of the dolines owing to the stronger leaching, while on higher levels and on the edge of the dolines, both the anion and the cation contents are higher. (*Fig. 4*).

The changing of humidity conditions of doline soils is quite important from the viewpoint of the life of the soil and that of the subterranean corrosion as well. The section close to the surface, which is richer in organic matter is usually wetter than the lower strata of the soil. The daily occurrence of convectional precipitation due to the drastic rise in temperature at midday is indispensable for the life of the soil, which is characteristic of the summer period. The soil humidity is higher in the southern part of the dolines. This figure is usually higher in afforested dolines than in those covered by soft-stemmed, grassy vegetation. The life of the soil is more intensive in the latter type.

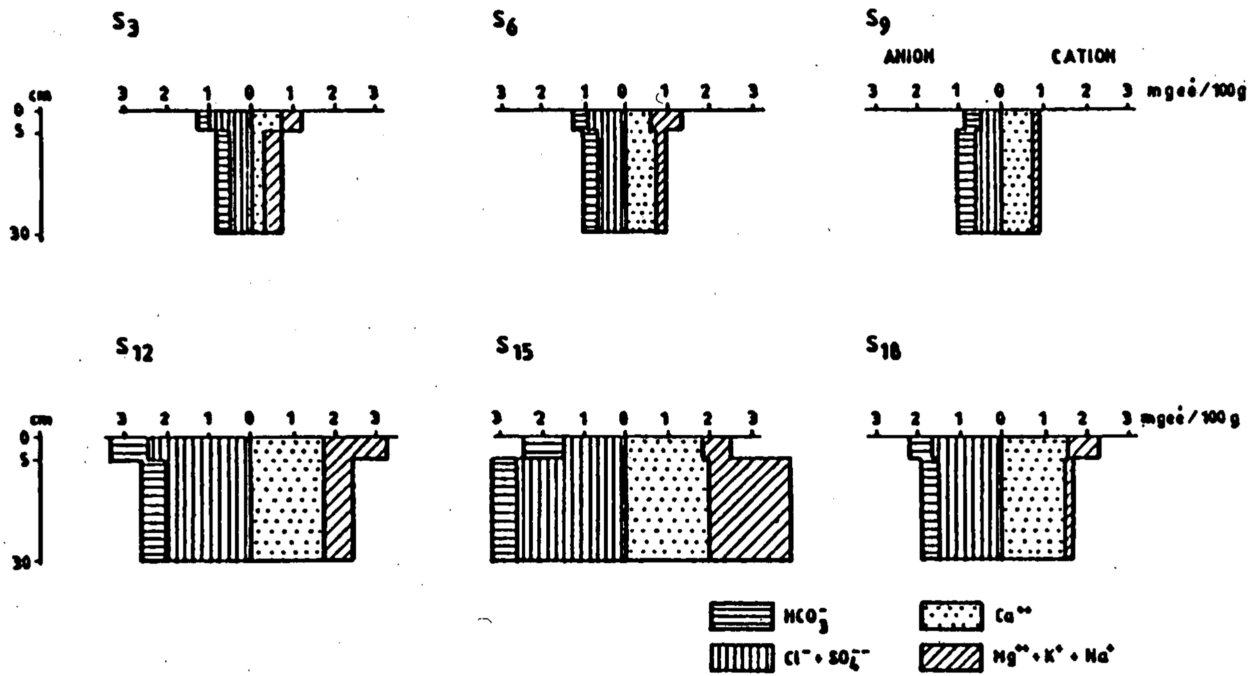


Figure 4 *The quantity of anions and cations which are soluble in water on the southern slope at level 3,6,9,12,15 and 18 metres*

The bacteria activity of the different dolina types

The pure numerical evaluation of the bacteria population - neglecting the environmental conditions - would provide misleading results. it is also a problem that the systematical registration of the number of bacteria according to their daily and seasonal changes in technically impossible. Therefore, the tests are only based on data obtained in 1-1 point of time. However, these data are useable for geomorphological investigations, because the purpose is to show the differences according to the expositions. Although the data collected in the same time cannot be absolutely accepted, they can be used in comparing them according to slopes, because the same percentage of error is probable in their comparation.

The bacteria activity of soils of the different dolina types was studied through the karstic soil samples from 5 cm and 30 cm depths; these samples showed different CO_2 production characteristics due to their different slope exposition. The samples gathered by 0.5 m levels from 7.5 m thick soil accumulations on the bottom of dolinas and karstic valleys were also examined. .

The samples of thin soil cover came from Aggtelek Hills. The dolina marked "A" is a grass covered (Nardo-Agostion-tenuis) "basin" type dolina, the dolina "B" belongs to the "valley" group and partly covered with pine forest and partly with grass (Nardus stricta). The distance between sampling points was 3 m.

The two dolinas of Aggtelek Hills are basically different concerning their vegetation cover; therefore, the distribution of bacteria population is also largely different. The distributional differences depending on the microclimate - which was analyzed above - are clearly observable in the dolinas that are not covered with wood. In this case, the soil is only deep in the dolina bottom, while the soil is thin (40-70 cm) at the sides due to the high slope gradient.

In the dolina bottom, where the soil mantle is thicker than 1.5 m, the number of bacteria is fairly high (4.0 and 5.2 x 10^6) at both levels, while it is generally smaller on the slopes. *(Figure* 5)

The differences in the soil-ecological conditions of the dolina without wood and that mostly covered with wood are most clearly demonstrated by the number of bacteria; further, it can be stated thereon that the soil phenomena are significantly effected by the macro-flora or the microclimate modified thereby.

The number of aerob bacteria per 1 gramm of soil at 5 cm soil horizon is the multiple of the values observed at same levels of unwooded dolinas. (*Fig.* 5) The difference between the two dolinas is already less remarkable at 30 cm horizon, but it is still large. This is explained by the fact that the trees - with grass vegetation - densely interweave the soil at 5 cm depth, modify its structure and create more favourable ecological conditions for the activity of microbes than the unwooded dolinas can have.

A similar type of difference between the two dolinas can also be observed when the number of anaerob bacteria is compared.

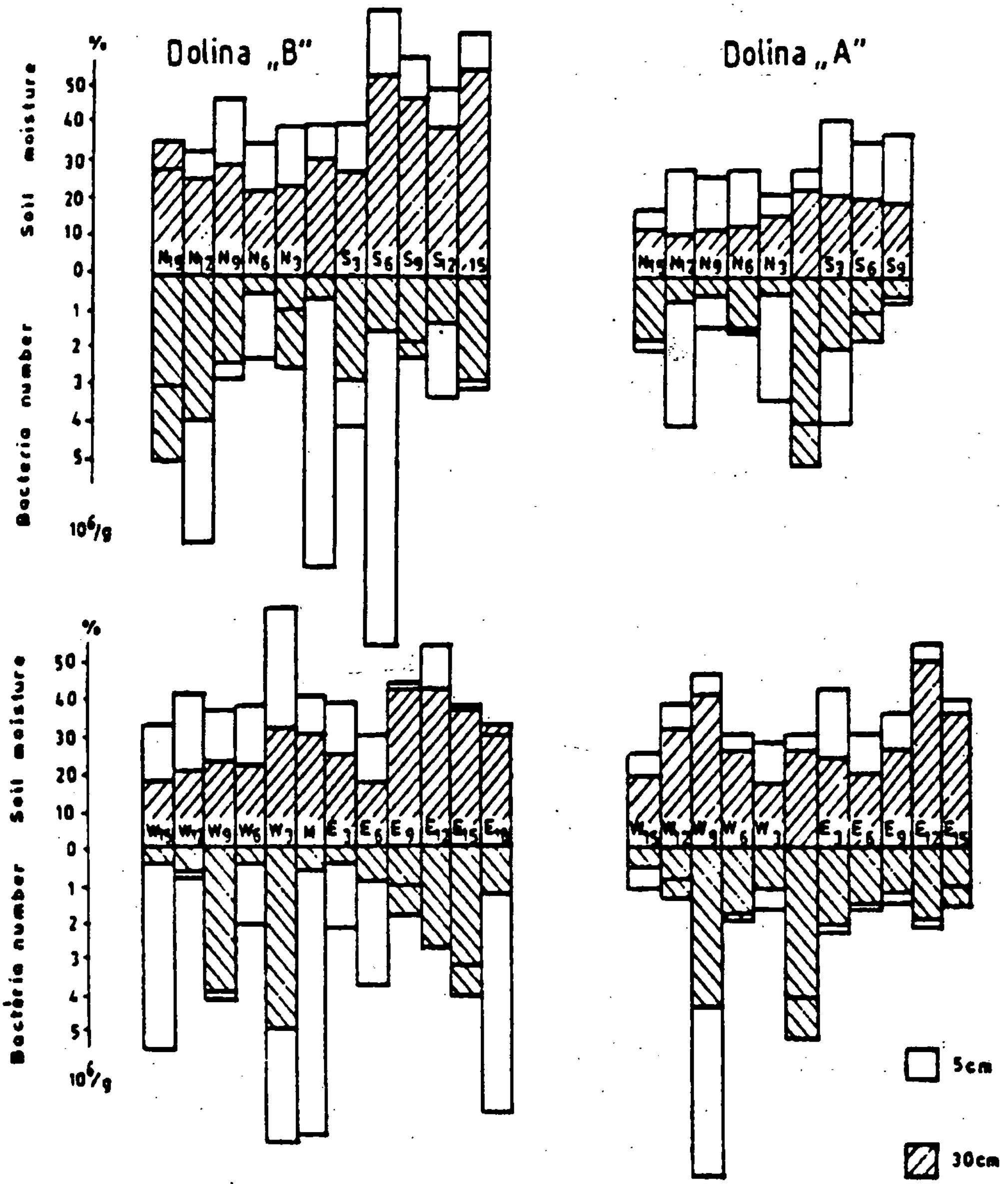


Figure 5 *Bacteria number and soil moisture in a grass covered doline ("A") and a pine covered doline ("B") at 5 and 30 cm depth*

In dolina "A ", in accordance with its higher moisture content, the northern slope (southern exposition) shows a large number of bacteria at 5 cm depth. At 30 cm, however, the number of bacteria declines, because the soil moisture content is lowest on this slope. (At 5 cm depth the daily convectional precipitations create favourable moisture conditions, although the irradation is fairly strong. However, at 30 cm the short time precipitations can not be so much effective due to intense irradation and evaporation).

On the southern slope (northern exposition), at deeper levels (3 m isohypse), the number of bacteria is even larger at higher levels, however, the development of a large number of population is hindered by the low soil temperature and the soil moisture exceeding 40 %.

The number of bacteria most reliably follows the changes of soil moisture on the western slope (eastern exposition); it increases or decreases accordingly. The moisture content and the number of bacteria grow until the middle of the slope (9 m isohypse), then they decline. The temperature maximum in the morning probably favourably effects the development of bacteria population.

The less extraordinary moisture content and temperature characteristics of the eastern slope (western exposition) result in a fairly uniform distribution of the number of bacteria. The soil is warmer there, the difference in the moisture content of the two soil levels is less explicit; therefore, the number of bacteria at 5 cm and 30 cm depths is almost the same throughout the slope and it generally linearly flows the moisture conditions.

In dolina "B ", covered with pines, the changes in the number of bacteria on various slopes can not be easily described, because - unlike in the case of dolinas - the moisture content of the soil is changed by the increased transpiration and the smaller temperature undulations due to the trees. The *higher value of moisture content and the smaller temperature undulations create favourable ecological conditions;* therefore, the number *of bacteria is normally larger at every level and soil depth in wooded dolinas than in open dolinas*. This dolina has deep soil cover at several points on the slopes.

On the northern slope (southern exposition), the number of bacteria is evenly growing from the dolina bottom upwards, at large following the moisture content.

On the southern slope (northern exposition), the lower temperature values are accompanied with higher moisture content; they do not favour the development of bacteria population. Exceeding the 9 m isohypse (where the soil is loose, and pebbly already from the surface, and where the number of bacteria at 5 cm depth is 10.4 x 10E6, the number of bacteria is relatively small on the southern slope.

The moisture content is lowest on the western slope (southern exposition), because open grass association grows there and the irradiation is effective. However, the temperature conditions are favourable, because the difference between the daily extreme values is not very large. This is favourable for the microbes, which explain the relatively large number of bacteria.

On the eastern slope (western exposition), the number of bacteria is increasing from the dolina bottom upwards, which is due to the similar increase in the density of wood.

At 3 m level the ecological conditions are still generally characteristic of the dolina bottom concerning the moisture and temperature; therefore, the number of bacteria is almost the same as on the dolina bottom.

The number of anaerob bacteria is smaller in the open dolina "A " than in the wooded dolina "B': It must also be noted that the number of anaerob bacteria is less reliable than that of aerobs; only they two together are useable for slope tendency studies.

The intensity of bacteria activity is basically determined by the temperature and moisture of the soil. The number of soil bacteria is naturally also effected by other factors such as the humus content of the soil, or the pH characteristics. While the humus content of the soil is growing in autumn in general, the number of bacteria is at its peak in summer. The pH characteristics of the soil, however, linearly follows the changes in the number of bacteria; the pH is highest in summer, when the decomposition of humus is most complete, and it is lowest in winter. The unfavourable physical and chemical state of the soil also decreases the number of bacteria.

REFERENCES

BÁRÁNY, I. 1985. Ökologische Untersuchung der Karstdolinen unter sonderre Berücksichtigung des Mikroklimas. Acta Geogr. T. XXV. pp. 109-130.

BÁRÁNY, I. 1987. Tendencies to change in compositions of karstic soil and the vegetation in the Hungarian Bükk Mountains. ENDINS No.13. pp. 87-92.

JAKUCS, L. 1964: Geomorfológiai problémák az Észak-Borsodi Karsztvidéken. (Geomorphological problems in the North Borsod Karst Region.) - Borsodi Földrajzi Évk. 5. pp. 1-12.

JAKUCS, L. 1977: Morphogenetics of karst regions. Adam Hilger, Bristol, 224 p.

MEZÖSI, G. 1985: Relief types and geomorphological surfaces on the interfluve of the Sajó and Bódva rivers. - Acta Univ. Szegediensis, Acta Geogr. 25. pp. 73-96.

MEZÖSI, G. - BÁRÁNY, I. - TÓTH, I. 1978: Karstmorphometrische Untersuchungen im Gebirge Aggtelek (Nordungarn). - Acta Univ. Szegediensis, Acta Geogr. 18. pp. 131-140.

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REDISSOLUTED FORMS ON STALAGMITES IN BELGIAN CAVES

Camille EK - László MUCSI

INTRODUCTION

According to Jakucs L (1985) pioneers work we investigated special redissoluted forms on the surfaces of stalagmites in Belgian caves. The formation of these phenomena is connected with the effect of acid rain according to Jakucs. We cannot prove this idea but we can also stay that these features are very young forms and the process is opposite to the general stalagmite formation. C. EK also discovered some similar features in Belgian caves in 1985 and after 10 years we have found these forms and a lot of new, young forms formed during this short period. We visited 3 different caves near to Liege where the coauthor L. Mucsi spent 1 year fellowship of Pharc ACCORD program in the Laboratory SURFACES, University of Liege.

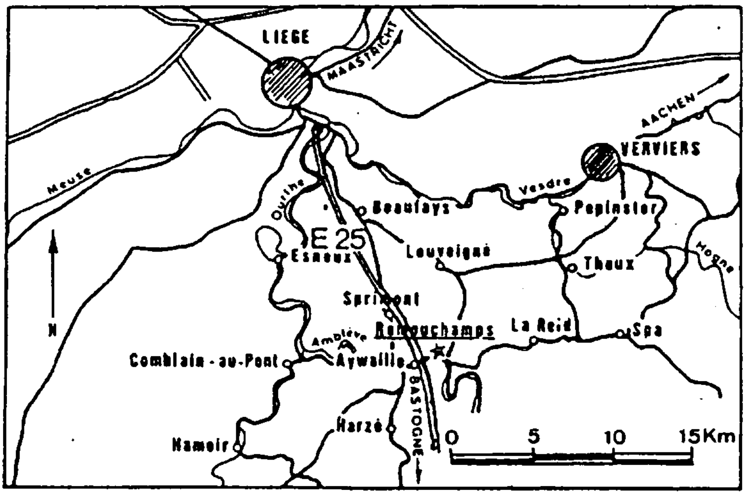


Figure 1 *Map of Belgium and the location of Remouchamps and Comblain-au pont*

Remouchamps

The Belgian town of Remouchamps lies some 20 kilometres south-east of Liege. The Ambleve, a tributary of the Ourthe river, flows through the village.The Ambleve passes through the town at an altitude of 130 meters, but the altitude of the surrounding area reaches 510 meters. Access to the village by rail or road is very easy (Fig 1). On the cave of Remouchamps different types of redissoluted form can be found. The forms are located at two different levels in the cave.

The most intensive rill formation can be investigated on the upper part of the cave above the Salle de Cathedrale in the Chamber of Shale. These recent forms clearly show the effect of resolution process. These rills are much longer than the same forms in Comblain-au-Pont and much more wider (1-2 cm). This chamber is near to the surface, the thickness of the roof is approximately 5-7 m. It is interesting that beside the redissoluted stalagmites we can also find increasing stalagtites. Therefore, the effect of the redissoluting water is in connection with local effects. On the wide rills, the , flowing water forms small phenomenon like meanders, therefore it is not so clear that this part of rills can be characterized as a redissoluted form rather eroded form. We know that these forms are recent forms and according to some factors we can calculate the maximal age also. Similar to the Hungarian cave Baradla, in Remouchamps was officially opened for tourists in XIXth century, at 1829. At this time the visitors used burning brands, whose smoke and ash accumulated on the wall. If the rills penetrate this grey-black coloured layer of the stalagmite, then we can say that the rills cannot be older the 160 years. On some bright stalagmites, it has to be much younger. This period is called post-soot period after L. Jakucs. On the bottom of the Salle de Cathedral some of redissoluted features can be found. These are also long rills, but opposite to the recently forming rills they are deep, narrow - forms rather than wide. Another different character is that they are jointing to each other (share edged corrosion), while the young rills on the Salle de Shale are spreading. Very important fact that these features cannot be touched by visitors because of their position along the tourist road (pavement) is high enough or they are located on unvisited chambers.

Comblain-au-Pont

In this cave the typical redissoluted form is the rill. All of this type of forms are located on the surface of stalagmites, or on walls covered by dripstones. The water drops reaching the wall or the stalagmite erode the limestone surface. From the spreaded water, small, linear forms are precipitated. These forms can be found on the lower surfaces in radial direction on splash-spray zone. The result of the kinetic energy of the dropping water is a small shallow which is filled by dropping water. In this phase, the kinetic energy of the water decreases, because the water drops are dropping into water instead of onto the dripstone surface. When the water drops filled the shallow (crater), the water surplus is flowing out, which induces the desolution. If the outflowing water can be solve the dripstone, small rills are forming. We have measured the pH of waterdrops in the case of

Comblain-au-Pont at a special dripstone form. The place where the water is dropping from is about 30 cm above the crater. At this point the pH was 7.5. From the crater, the water is flowing down on the dripstone surface in vertical = direction and the distance between the crater and the new place of the formation of water drops is approximately 20 cm. At this point the pH was 7.8. The temporal difference between the falling down of the upper waterdrops and the occurrence of the water drops below is about 1 sec. The significant difference between the pH values and the short time of the chemical process indicates that this process is very fast and strong.

On the second chamber there is a great group of stalagmites. It is interesting that the small craters do not exist on the surface of stalagmites, because of the small angle of the incidence of water drops. On this surfaces long and relatively deep rills are being formed. In all cases the desoluted stalagmite are indicated by a new, brighter colour.

Ste-Anne-cave Tilff

There are also some typical redissoluted features in this cave. The effect of this process is very intensive on all redissoluted forms. These forms can be compared to the similar phenomena of Remouchamps cave located in Salle de Schiste. The deepness of this craters is ranging from 3-5 mm. Because of the former investigation of C. EK (1985) we can state that these form are very young forms. In some cases the distance between the place of dropping water and the crater is less than 2 cm, therefore the effect of corrosion has to be stronger than the effect of kinetic energy. The. effect of redissolutoin is the strongest in the surrounding of the water, the radius of this zone is about 5-7 cm, but the length of the rills is sometimes greater than 50 cm. The effect of redissolution can be seen not only on stalagmites but on soda-straw dripstones whose tips are clearly being recently corroded. The shape of this rills is widening at the bottom, which can be the result of the redissolution getting stronger. On the surroundings of the crater, rather the deepening effect is more significant, while in the = leeward zone the widening effect. The zone, which is covered by redissolution rills, can be 30-50 cm wide. If there are 3-4 craters near to each other then this zone can merge and in this case the effected zone can be 1 m wide.

The most frequent case, if more rills carry away the aggressive water of the crater the effect is divided. We have found such crater, at which just one rill is existing, in this case the effect of aggressive water concentrated into this rill, therefore it becomes deeper than wider. The new brighter colour is also an important characteristic of the redissoluted forms in the Ste-Anne cave, like the other two investigated cave.

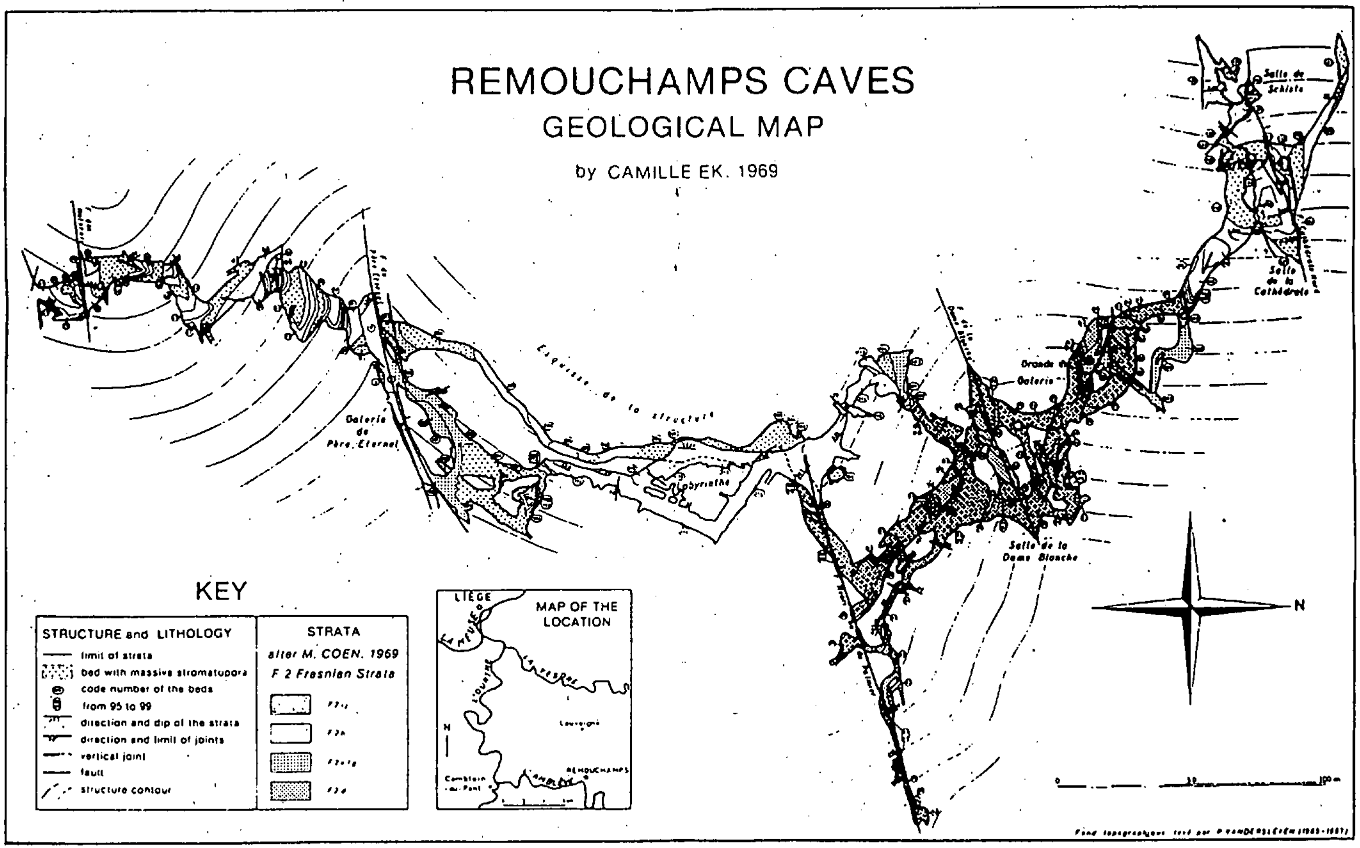


Figure 2 *Geological map of Remouchamps Caves (C. Ek, 1969)*

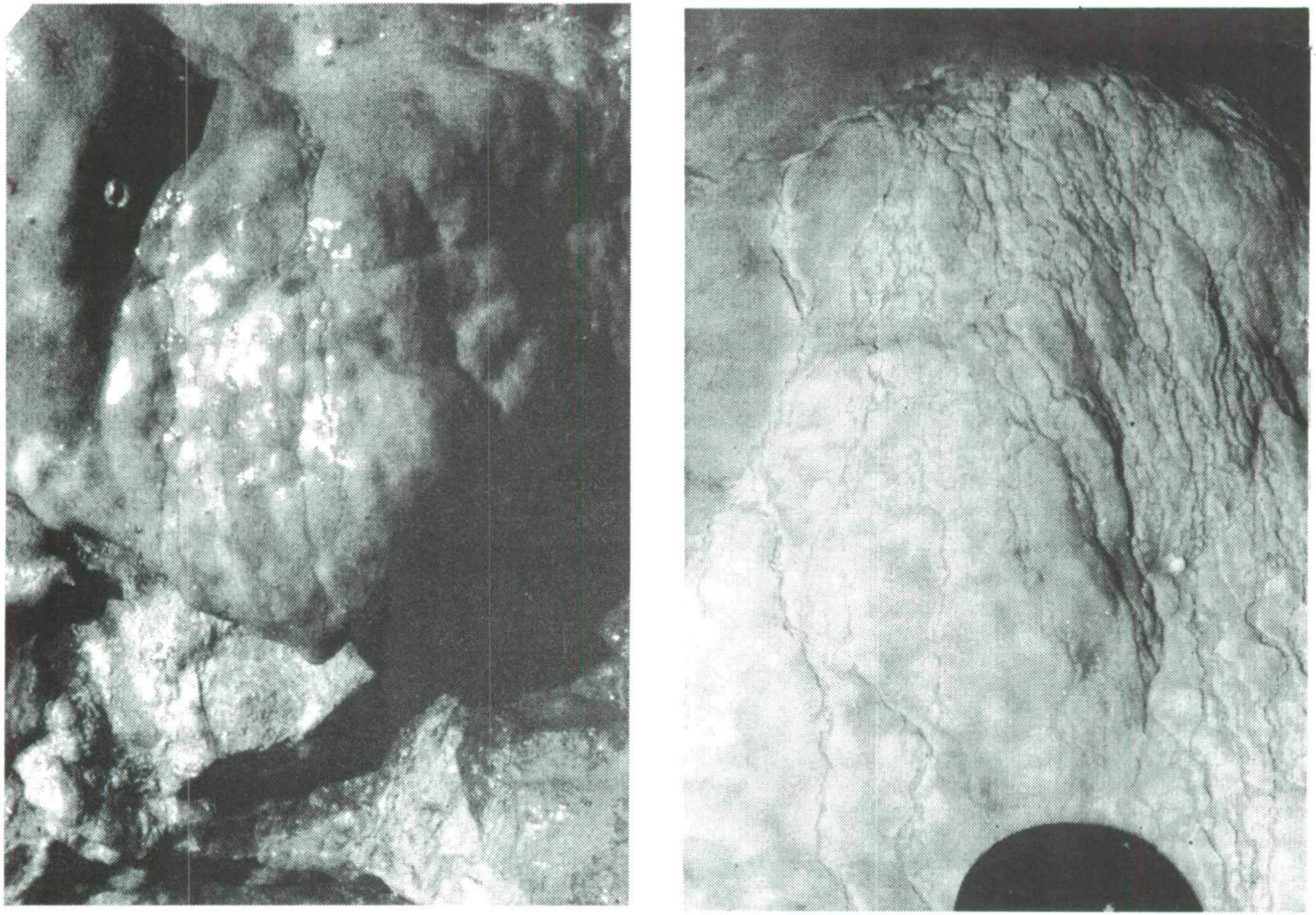
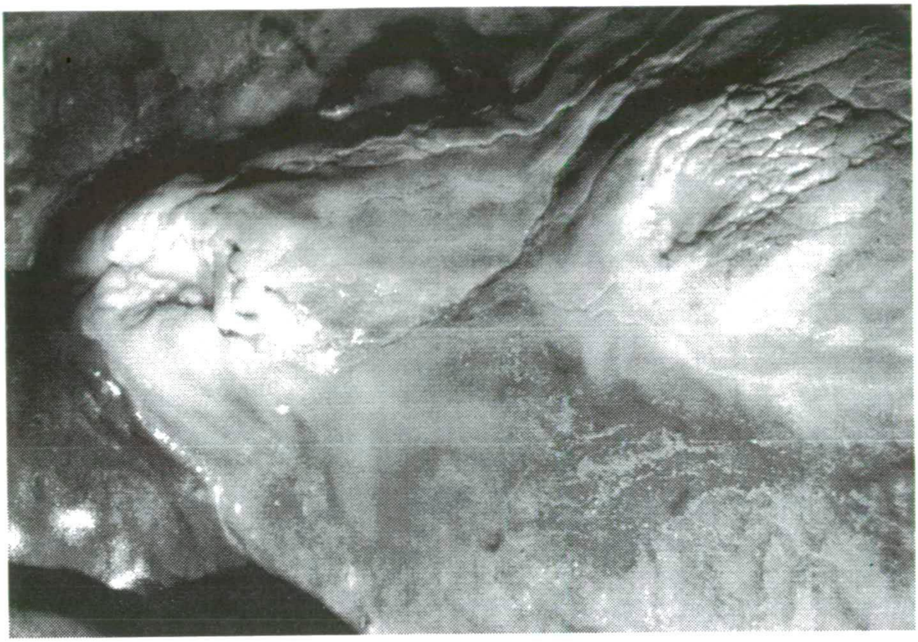


Photo 1-2 *Redissoluted speleotherms in the Remouchamps Cave and in Cave Comblain au Pont*



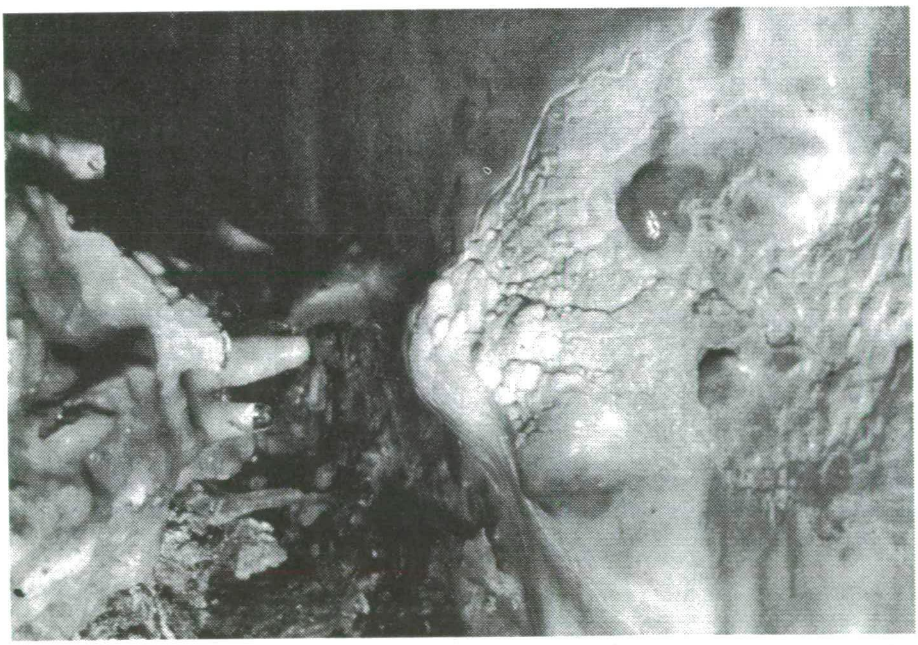


Photo 3-4 *Redissoluted speleotherms in the Cave Comblain au Pont*

Conclusion

According to our common study we can say that there are much more redissoluted features in the Belgian cave then 10 years before. The decreasing number of these forms shows that we have to pay more attention to the environmental monitoring and protection of limestone surfaces and caves, because the karst areas are very sensitive for the environmental changes and polluting materials.

References

Jakucs L.: Az újtípusú cseppkődegradációra vonatkozó legújabb kutatási eredmények. Összefoglalás. (The latest investigational results concerning the dripstone-degradation of a new type.) = Oktatási intézmények karszt- és barlangkutató tevékenységének 2. országos tudományos konferenciája. Szombathely, 1987. p. 53-54.

Mucsi L. 1993: Acidification of some soiltypes in Bükk Mountains. Acta Geogr. Szeg. Tom. XXXI. pp. 47-53.

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FACTORS OF THE ENVIRONMENTAL SYSTEM OF KARST

Ilona BÁRÁNY-KEVEI

INTRODUCTION

The relevation of the environmental system plays on increasingly important rôle in geomorphological research. It is especially true for the ecological systems of karst regions, since karst is an open system.Here the changes in environmental effects are asserted rapidly. Chemical, organic and other materials are carried by seeping water without changes to the deeper karstic thereby rock modifying karst development. In spite of the fact that the limestone can reduce the effects of acid deposits by its buffer capacity, long-term unfavourable effects can also modify subsurface processes. Signs of this process can be found in several Central European caves in the form of characteristic dripstone degradation. This phenomenon is most frequent where the rock layer is very thin above the cave and there is not enough flow path to buffer the seeping water.

The quality of karstwater both in caves and karst springs has been investigated comprehensively by karst researchers. However, there are fewer investigations which define the quality of seeping waters. MAUCHA (1930) and JAKUCS (1986) investigated the quality of seeping water in a few Hungarian caves. According to Jakucs's measurement, the SO_4 content of seeping water has increased significantly in Baradla Cave in Hungary in the last few decades.

DISCUSSION

The investigations mentioned above have only strengthened the intention of the author to widen her examination to the whole karst system. The most important elements of the karst environmental system were summarized by Y. DAOXIAN (1988).

According to Daoxian, karst is a complex system of rock, soil, organisms as well as energy. A.S. GOUDIE (1986) deduced the development of the ecosystem of limestone surfaces back to the bedrock, climate, time of the effect of climate and human activity.

In my opinion, which is similar to opinion of the above mentioned authors, the karst-ecological system starts at the air layer near the surface as well as plants, which cover the karst surface and it finishes at the karst water system or karst springs (*Fig.1.*).

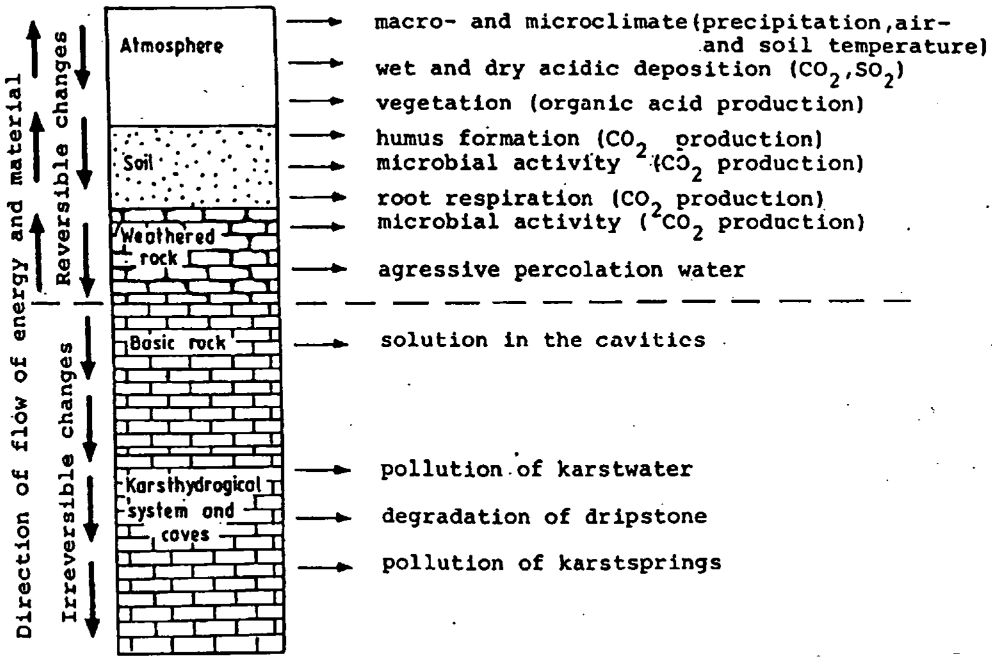

Figure 1 *Schema of karstecological system*

The water and energy pass into the rock body through the soil and can reach the caves where accumulation occurs. The seeping water, depositing its calcium, feeds the karst water system. During infiltration, the seeping water goes through significant changes. These changes (favourable or unfavourable) can be traced to the border with soil and rock. They are reversible to this border since after it there are only a few opportunities to modify the quality of karstwater in caves. The change in solution intensity can be so significant that it can be present in morphological aspects e.g. change in the development of dolines, dripstone degradation.

The investigation of karst-ecological system is very important because of the solution of limestone has biogenic character (Jakucs, 1988). The effect of the biosphere takes a more significant role in terrain evolution on limestone than on other rocks. Only of few researchers consider the phenomena of karst as a biogeomorphological phenomena (Viles,H.A.1988).For example the limestone may be coral limestone (biogenic origin), where the microflora take place directly in the formation of karstic phenomena e.g. root karren and travertine. Concerning to the above explanation, it may be considered that biogenic processes are very important in the development of karst surface because billions of microorganisms are active in karst soils (Kevei-Bárány,I.-Zámbó,L.1986). This is determined by considering the characteristics of karst soils,where microorganisms decompose organic materials in faintly acid conditions chemical properties of the soil are changed by metabolic products and CO_2 is formed in great quantities during decomposition. These processes determine the chemical property of seeping water and consequently, the intensity of karst corrosion.

The mentioned processes above are intensive near the karst surface and therefore their investigation at this level is a significant task. In my former studies a number of factors of the ecological system were examined in karst dolines; in fact solution dolines can be considered as most important landforms on Hungarian karst surfaces. In microregions, microclimate is the most significant ecological factor. The microclimate is effective on vegetation by the differences in rising hot air layer.

The extreme changes in temperature in karst dolines do not favour arborescent vegetation therefore the majority of dolines are covered by grassy vegetation. This type of vegetation increases the extremity of surface temperature which is turn effects the soil temperature. Differences of 10-12 °C can appear in the upper soil layer in the southern exposition of dolines. In the southern and western exposition, drought-resistance vegetation survive, in the eastern and northern exposition hydrophytone vegetation survives extreme conditions. The soil temperature differentiates between the number of soil bacteria on distinctive doline slopes (*Tab. 1*). These results prove the researchers must take these factors into consideration during the investigation of the karst ecological-system.

Number of aerob bacteria in a Bükk doline without forest (Million)						
Level	3 m	6 m	9 m	12 m	15 m	18 m
S slope	1,9	1,7	0,7	-	-	-
W slope	11,0	1,9	4,3	0,8	0,4	-
N slope	0,4	1,4	0,5	0,6	1,7	2,9
E slope	2,3	1,6	1,2	1,9	1,5	-
Number of aerob bacteria in a Bükk doline with forest (Million)						
Level	3 m	6 m	9 m	12 m	15 m	18 m
S slope	2,9	1,5	2,2	1,2	2,9	-
W slope	5,0	0,4	4,0	0,8	0,4	0,3
N slope	2,6	0,5	2,4	4,0	5,1	-
E slope	0,4	0,8	1,8	2,7	4,0	1,1

Table 1.

The soil is one of the most important ecological factors in the so called "hidden open karst" (I. Bárány and L. Jakucs 1984, hidden open karst=karst surface covered by soil). This thinner or thicker soil layer can strengthen or buffer the unfavourable exogenic effects. Therefore the physical quality and chemical property of soil are very important in karst processes. Both can be modified by the above detailed factors (microclimate, vegetation, bacterium activity). The permeability depends on the physical characteristics of the soil. Usually, clayey soil with low permeability is frequent in the investigated dolines. Chemical properties were characterized by pH value as well as the quantity of water soluble anions and cations (I. Bárány-Kevei 1992). With the help of the comparison of pH (H_2O) and pH (KCl) we can show the trend in the change in pH value. With the help of data the trend of acidification can be proved in Hungarian karst soils but the strength of acidification is different in distinctive soil types and regions. Former investigations of soil samples from the Aggtelek and Bükk Mountains were completed by the analysis of soil samples from Mecsek Mountains (situated in the southern part of Hungary) in 1992. In this region (Triassic limestone, 3-400 m above sea level) the tendency of soil acidification is stronger than in the Bükk Mountains. The difference between the pH values of the soil samples from doline slopes greater in the Mecsek Mountains (*Fig.2*).

The cause of this fact may be that at lower elevation more harmful materials can be found in the air and carried away from nearby industrial region to the limestone surfaces. Therefore, soil acidification can be related to the effect of human activity (industrial and human waste materials). During the imission of waste materials these materials are washed by precipitation into the upper soil layer and result in more intense weathering and soil acidification.

The quantity of water soluble anions and cations gives information about the ion composition of karst soils. In my former studies, detailed analyses can be found. In this study, analysis of samples from the bottom of dolines is presented. Comparing these data we can say that there are less water soluble cations in the soils of the Hungarian dolines than in the soils of dolines in Croatia (*Fig. 3*). This fact proves that soils of dolines are more basic in Hungary than in Croatia as a result of microclimate and human activity.

RESULTS

The differences mentioned above in microclimate, vegetation and soil take a very important role in the development of the karst-ecological system.

1. Extremities of surface temperature stunt the development of arborescent vegetation. The euryoecic grassy vegetation survives the extreme changes in temperature.

2. The air temperature affects the soil temperature and daily differences can be 8-10 °C in the upper soil layer.

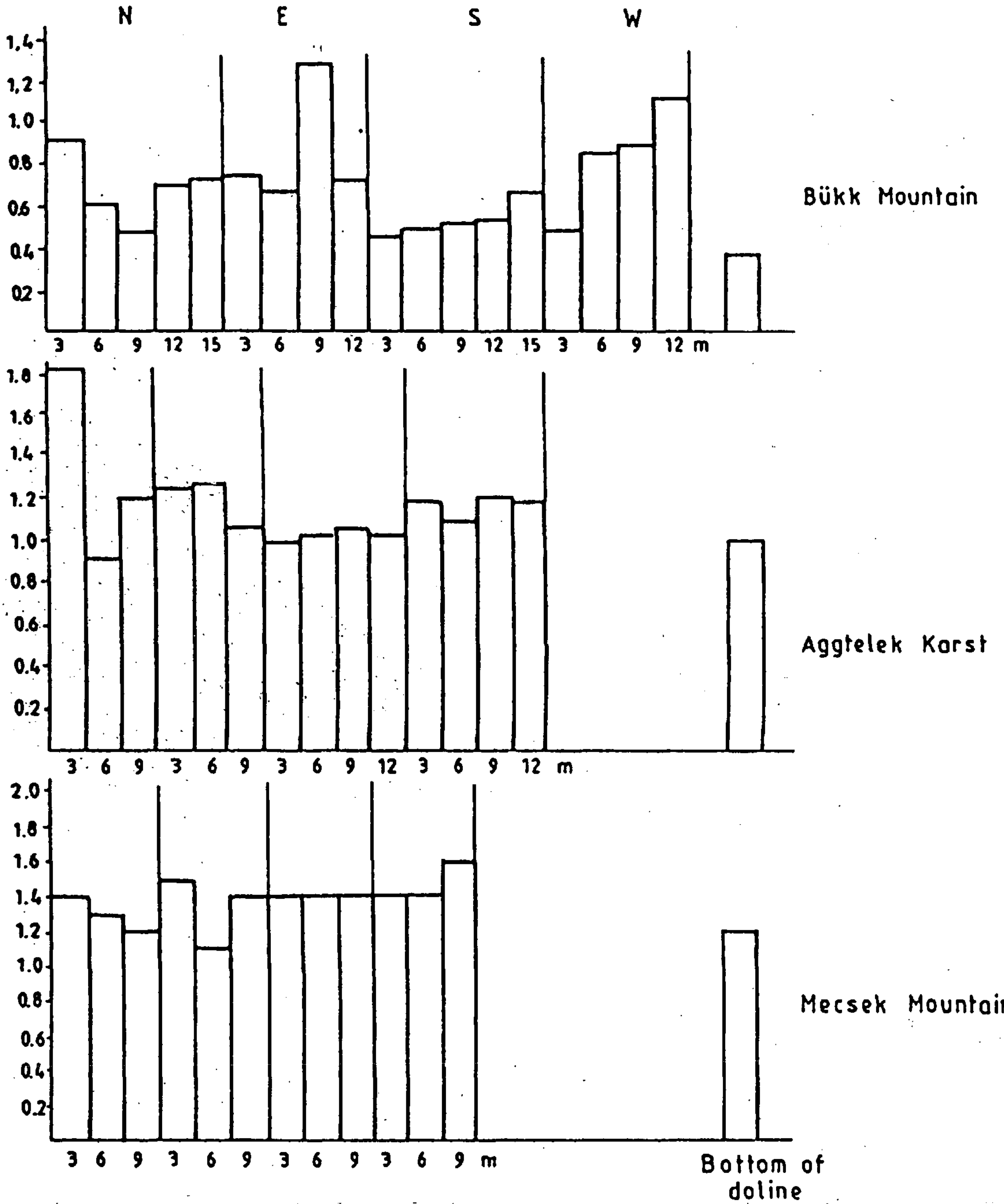

Figure 2 *Differences between soil pH values suspended in water and KCl at the depth of 5 cm on the different slopes*
3,6,9,12 m = relatively level in the dolina

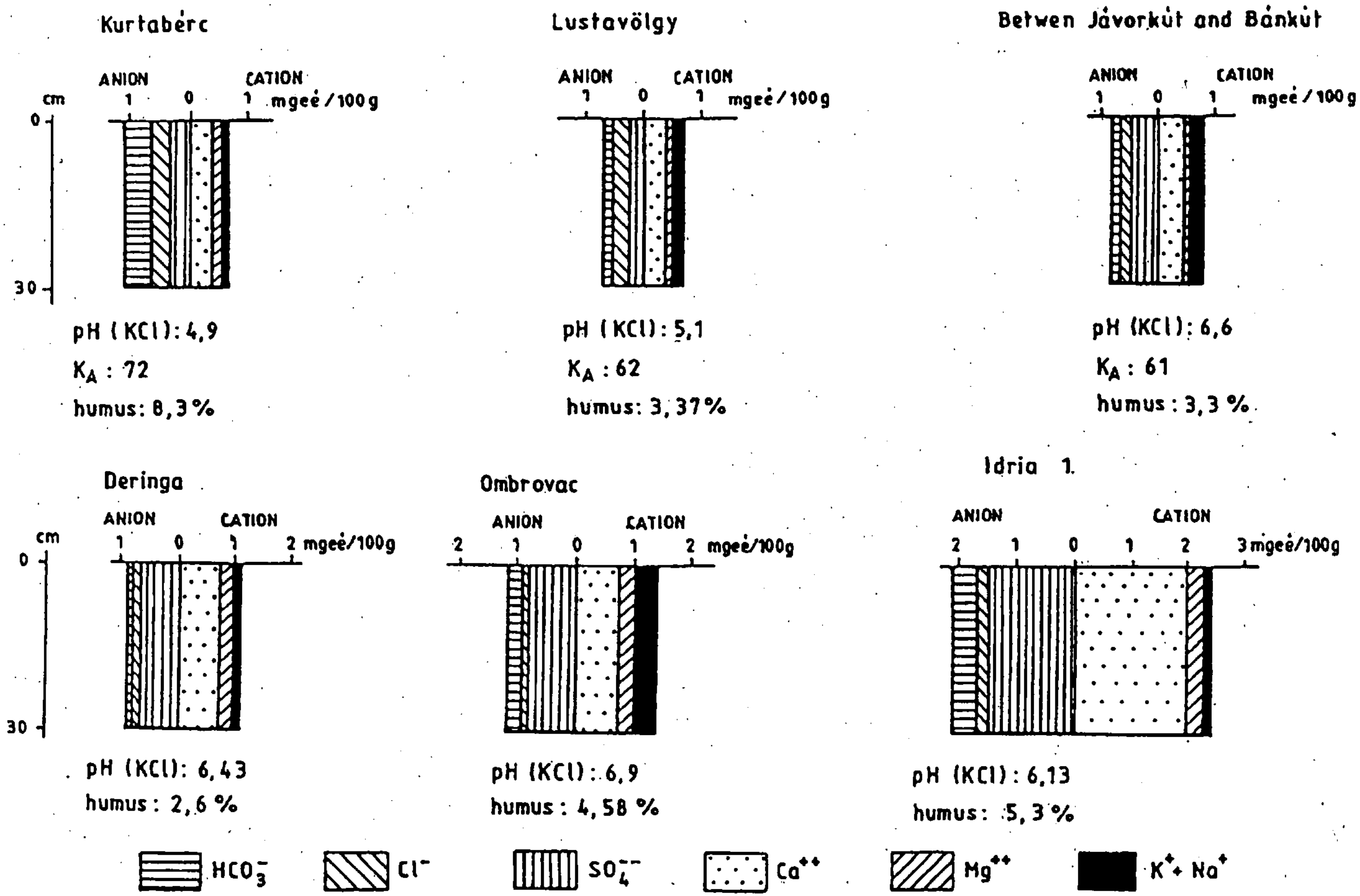

Figure 3 *Water soluble anions and cations in the bottom of dolina in the Bükk Mountain and in the Dinaric Karst*

3. The extremity of soil temperature differentiates the intensity of bacterial activity and consequently the quantity of the forming CO_2. Apart from temperature, humidity also has an influence on bacterial activity. The greatest population can be found in the upper soil layer and directly on the weathered surface of bedrock.

4. The chemical property of soil shifts toward acidification. This trend is stronger on lower elevations than lifted karst surfaces. At lower pH values soil erosion is also stronger. The chloride and sulphate anion content increases in the seeping water and strengthens the intensity of corrosion.

5. If the path of seeping water is short enough then it can be the cause of dripstone degradation. The phenomena can be observed in numerous caves.

With the help of the above mentioned facts I would like to suggest that further attention he given to the analytical investigation of the inner functions of the karst-ecological system.

REFERENCES

BÁRÁNY-KEVEI,I.(1992): A karsztökológiai rendszer vizsgálata bükki dolinák példáján (Investigation of karstecological system on the basis of Bükk dolines) A Bükk karsztja, vizei, barlangjai, Miskolc I. kötet pp. 25-38.

BÁRÁNY-KEVEI,I.-JAKUCS,L.(1984): Szempontok a karsztok felszíni formáinak rendszerezéséhez, különös tekintettel a dolinák tipusaira (Thesis of systematisation of karstlandform special attention to dolines) Földr. Ért. XXXIII.évf. 3. füzet. pp. 259-265.

BÁRÁNY-KEVEI,I.-ZÁMBÓ,L.(1988): Study of the relationship between bacteria activity in karstic soils and corrosion Annal. Univ. Sci. Budapestiensis de Rolando Eötvös Nom. Sectio Geographica. Tom. XX-XXII. pp. 325-333.

DAOXIAN,Y.(1988): Karst environmental systems. Proc. of IGU Study Group Man's Impact on Karst. Sydney pp.149-163.

GOUDIE,A.S.(1986): The human impact.Oxford; Basil Blackwell.

JAKUCS, L. (1986): A savas esők (ülepedések) hatásának nyomai a barlangi cseppkövek visszaoldódásában (Traces of acid deposition impact on the resolution of cave dripstones) Karszt és Barlang I. füzet pp.15-22.

MAUCHA,R.(1930): Az Aggteleki cseppkőbarlang vizeinek kémiai vizsgálata (Chemical investigation of waters of Aggtelek dripstone caves) Hidrol. Közl. X. kötet pp.201-207.

VILES,H.A.(1988): Organisms and karst geomorphology.in.: Biogeomorphology.Basil Blackwell.pp.319-350.

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HUNGARIAN TRAVERTINES

Ferenc SCHWEITZER - Gyula SCHEUER

ABSTRACT

The travertine levels, which overlie each in a step-like fashion can be divided into two groups (the horizons of travertines were numbered from the lowest point (Budapest, Rómaifürdő, 107 m a.s.l.) up to the highest (Buda Mountains, Szabadsághegy-Normafa, 493 m a.s.l.), so their symbols are T_1 — T_{12}. First are the members of the lower series deposited close to each other on the valley-side terrace between 107 and 240 m a.s.l. (horizons T_1 — T_7). Second are the members of the higher series deposited on older geomorphological levels (T_8 — T_{12}) which succeed each other with considerable local height difference and are lithologically different from the lower series.

Correlations between the lower travertine series and the terraces of the Danube and its tributaries.

Travertine T_1 can be associated with the first flood-free (II/a) terrace, travertine T_2 with the second flood-free terrace (II/b), and so on up to horizon T_5, which is deposited directly on the terrace No. V. north of Budapest. The travertine horizons T_5, T_6 and T_7 are best represented in the Gerecse Mountains, where they lie on terraces V, VI, VII of the Danube and occasionally on those of its tributaries.

The absolute age of selected travertines deposited on the terraces was determined by means of the Th/U method (PÉCSI, — OSMOND, J.K. 1973), and gave ages of 70 000 years for travertine T_2 (Óbuda terrace II/b), 190 000 years for travertine T_3 (Kiscell Plateau) and more than 350 000 years for the travertine T_4 (Vértesszőlős — Buda Castle Hill).

According to the palaeomagnetic data from the loess strata intercalated in the travertine T_4, is younger less than 700 000 years of normal, while the T_5 horizon is older than 700 000 years of reversed magnetic polarity.

The fauna found in the travertines of the Buda Castle Hill (T_4) and at Üröm-hill (T_5) can be referred to the Middle Pleistocene and Upper phases of the Lower Pleistocene (JÁNOSSY, D. et al. 1976; KROLOPP, A. 1966).

In the Gerecse Mountains travertines T_6 — T_7 proved to be of Upper Villányium — Lower Pleistocene (Kislángium age) based on microfauna collected by SCHWEITZER, F. and determined by JÁNOSSY, D. (1978).

Travertines T_9 and T_8 are deposited on the lower (270-250 m) and higher (360-300 m) pediments abutting the valley sides of Szabadság and Széchenyi Hills. Preceding their formation, the Buda Mountains rose considerably at the beginning of the Upper Pliocene, causing a lowering of the karst water table and the generation of new karst springs along the bank line of the lower pediment.

The oldest travertines of the Buda Mountains (T_9 — T_{12}) are deposited on sands and gravels of Upper Pannonian age, the T_{10} is a greyish lacustrine-marshy formation, whose micro- and macrofauna as well as position suggest it to belong to the "Sümegium" of the Upper Pannonian. Travertine T_{11} is deposited on the highest Pannonian marine terrace at a height of 440-450 m above sea level. It is suggested that at the time of the formation of travertines T_{11} and T_{12} the Buda Mountains had risen somewhat above the level of the Pannonian inland sea and that the marine terrace may be associated with karstic springs action.

In the Buda Mountains the travertines suggest the existence of 12 geomorphological surfaces, which are indicative of the degree of tectonic uplift that has taken place since the Upper

Pannonian. Based on the position of the various travertines, we would estimate 70 to 80 m of uplift took place during the Upper Pannonian, 80 to 100 m during the Upper Pliocene and 130 to 140 m during the Quaternary, within which 6 to 8 m can be assigned to the recent (Fig. 1).

INTRODUCTION

In Hungary travertines are quite common; they are in an overwhelming part associated with karst mountains or portions of mountains. Their cadastral survey contains more than 500 independent occurrences. In some mountains their significance is great from the viewpoints of archeology, faunistics and geomorphology. By origin they are deposits of karst and karstic thermal springs (*Fig. 1*).

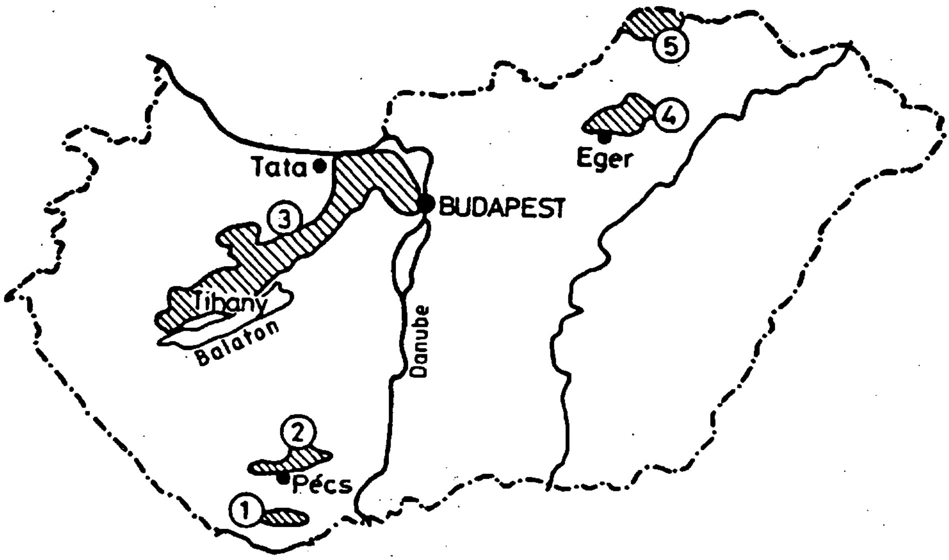


Figure 1 *Layout of the investigated area 1 = Villány Mt; 2 = Mecsek Mt; 3 = Transdanubian Mt; 4 = Bükk Mt; 5 = Aggtelek Mt*

Travertines are also common in the neighbouring countries, moreover, all over the world. In Czecho-Slovakia, for instance, the number of independent occurrences exceeds one thousand (KOVANDA, J. 1971). Several recent travertine occurrences are world-famous natural rarities (Yellowstone Park in the United States, Plitvice in Yugoslavia, and Pamukkale in Turkey).

The study of travertines in Hungary revealed the various types and a kind of diversity not experienced at other groups of rock. Travertines may be hard, compact, unstratified, unconsolidated stratified, or have interbeddings. It is related to the origin of springs depositing them and also to the chemical composition of spring water, particularly its dissolved calcium content, the geomorphological position of springs and their environs.

To interpret and explain the phenomena of travertines of extremely diverse expression and age, the recent travertine occurrences in Hungary and the neighbouring countries, we must directly observe and interpret the intricate forms and the factors inducing them. Moreover, relationships were sought between lime accumulation (carbonate dynamics) and the physical-chemical properties, as well as between lime accumulation and the activity of springs and climatic conditions.

MAIN HYDROGEOLOGICAL AND GEOMORPHOLOGICAL STATEMENTS CONCERNING TRAVERTINE FORMATION

1. The concept of springs of travertine deposition cannot be narrowed down to karst and karstic thermal springs, as had been believed by some experts, since travertine may deposit from any type of water (regardless of origin and temperature) which contains more or less dissolved calcium hydrogen carbonate.

Role of Travertines

The springs and waters of travertine deposition can be referred to five major classes:

a. Cold karst springs and karst water streams (below 14 °C).

b. Lukewarm and warm karst springs and their waters (stream, swamp).

c. Soil, layer and crack springs.

d. Postvolcanic warm or hot springs and waters.

e. Mixed or heterogeneous springs and waters (e.g., gas is postvolcanic [CO_2] and water is ground or karst water).

2. This is the first paper to classify and tabulate springs of travertine deposition from the hydrogeological and water chemical aspect. The tables provide a quick overview and basic information for researchers.

3. Travertine occurrences also exist, the origin of which *cannot be connected with the very frequent karst waters*. They are mainly attributed to springs of postvolcanic activity. Moreover, in restricted areal distribution travertine is observed in the vicinity of certain free and confined groundwater springs too. Its significance, however, is not considerable. Especially important are the travertines accumulated by CO_2 and mineral springs originating from postvolcanic activity.

4. The abundant material for comparison suggests that travertine occurrences of postvolcanic origin are frequent on a global scale. In Hungary, for instance, the origin from thermal water adds special features to the travertines of the Transdanubian Mountains.

5. Travertines of major areal extension are usually found around *springs of great discharge*. In addition to discharge, the time factor plays a remarkable role, as well as the geological stability of springs, i.e. their issuing in approximately the same spot.
In the case of numerous karstic thermal springs travertine deposition was not observed. This can be explained by the unfavourable environmental conditions — primarily the geomorphological position of issue — for accumulation.

6. The *deposition* of travertine series is a joint result of complex processes. The ratios between the most diverse geomorphic factors, environmental conditions, the time factor, and the interactions between the properties of the depositing spring jointly form and influence the origin and development of travertines.

7. From the *bedding conditions* and relative positions of travertines formed from the Lower Pannonian to the Holocene, conspicous features can be found which root in the character of the karst hydrodynamic system of the Transdanubian Mountains, its paleogeomorphology and structure. These features, among others, include:

a. karst springs generally issue from the deepest lying karstic rocks of the topography;

b. contemporaneous springs issue approximately at the same elevation (15 m);

c. accordingly, in an areal unit, limestones of similar age may have been formed at similar altitudes with minor differences, with the exception of travertine formations of tetarata type;

d. in most cases travertines form sequentially in a step-like fashion in certain valley cross-sections and are associated with characteristic geomorphological surfaces.

The hydrogeological and geomorphological positions of travertines show that springs depositing travertines issue, in most cases, from the lowest-lying karstic blocks of free surface. Elsewhere karst springs are absent since the permeable karstic rocks are buried under impermeable formations of great thickness, or karstic rocks have such great elevations which rise above the karst water table governed by the hydrodynamic balance of the karst system.

The formation of the step-like travertine horizons can also be explained by the denudation increased by the uplift of permeable layers inhibiting the issue of water from the permeable karstic horsts. Issuing water found its way along the structural faults typical of the two mountains.

8. The *typology* of travertine series — according to the topographic location of their origin, lithological properties and the analyzed karst hydrological processes — enabled, for the first time in the international literature, judgement of the chronological significance of travertines and their role in the reconstruction of geomorphic evolution.

The possibilities for the deposition of travertines and for the issuing of the karst springs depositing them are associated with four typical geomorphological karst hydrological situations. Several of the four basic types differentiated can combine to form a fifth type.

8.1. *Lacustrine-paludal type travertine series deposited on alluvial surfaces*. They deposited at the base level where on the adjacent terrains of flood-plains enough water was present creating even lakes and swamps. Travertine precipitated and accumulated from springs cutting through fluvial deposits. In many of the cases karst springs were fed by buried horsts covered by flood-plains deposits of moderate depth. In some instances, however, the springs depositing travertine issued immediately from the sides of outcropping karstic horsts on the flood-plain margin. The model outlined here of travertine formation, according to our observation, is not so general or exclusive in the Hungarian Mountains as was represented in earlier interpretation (*Figs. 2 and 3; Pict. 1*).

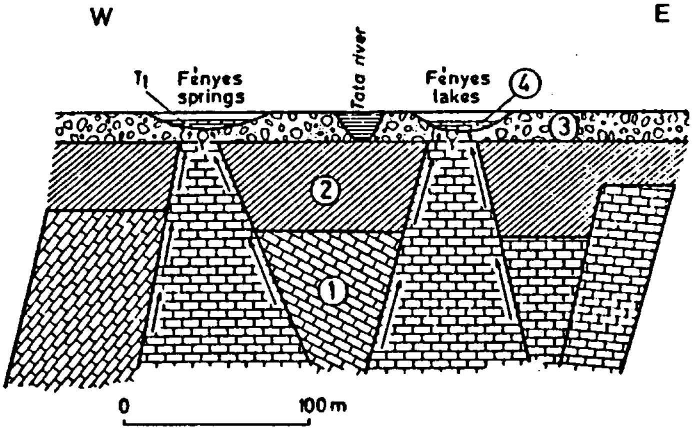


Figure 2 *Flood-plain-lacustrine-marshy travertine formation associated with spring issuing from covered horst through fluviatile sediments.* 1 = permeable Triassic sediments; 2 = impermeable Tertiary sediments; 3 = recent sediments of the Általér; 4 = travertine.

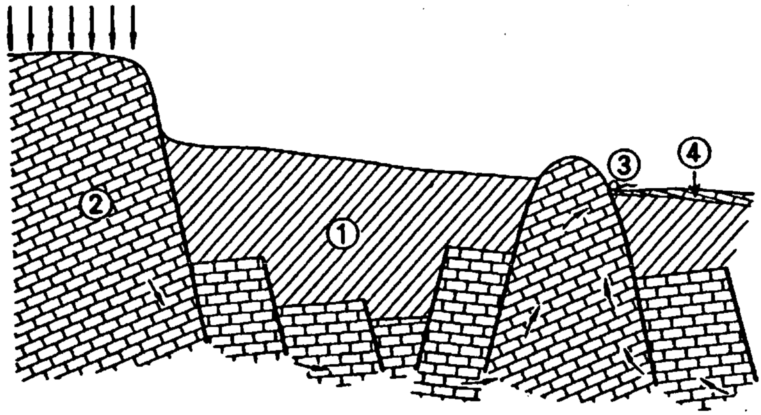
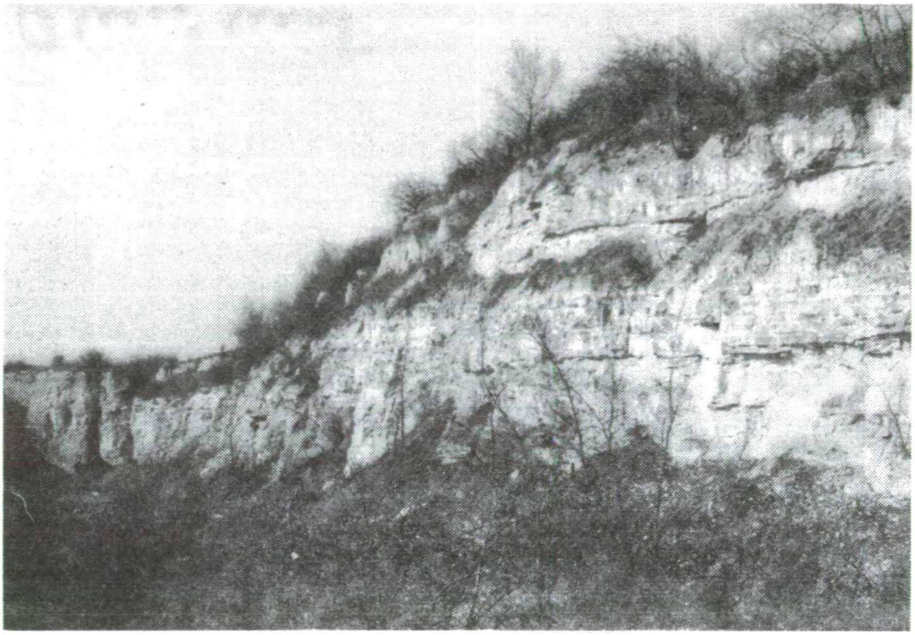


Figure 3 *Travertine associated with springs issuing from horst side onto flood-plain.* 1 = impermeable Tertiary sediments; 2 = permeable Triassic sediments; 3 = karst spring; 4 = travertine.



Picture 1 *The Lower Biharian lacustrine-paludal travertine T_6 (at 220 m a.s.l.), Pilis Mts. Hungary.*

8.2. *The travertine series of spring cone type.* In a geomorphological position similar to the previous, but on a lower terrace, surfaces this type of formation. In the case of this type spring water has a high mineral salt content and travertine precipitation is so intensive even at the spot of issue that a spring vent forms which rises into a cone, while on the slopes of the spring cone travertine accumulates in inclined layers. As a matter of fact, the spring cone can be destroyed or opened by outward effects. The spring issues on the cone top as long as it is made possible by hydrogeological conditions. Subsequent to hydrogeological change the development of the spring cone stops and on a lower surface — e.g. a terrace — the accumulation of a new spring cone may begin (*Fig. 4; Pict. 2*).

8.3. In the case of *travertine formation on valley sides* karstic rocks are buried under impermeable layers on the lower section of the valley side, therefore the spring can issue only above the base level, on the slope. Under such geomorphological or hydrogeological conditions the travertine precipitating from the karst spring accumulates on the slope, incidentally covering one or two surfaces. Here it is possible that during a longer period of travertine deposition two geomorphological surfaces of various age are buried under identical travertine mantles (*Fig. 5; Pict. 3*).

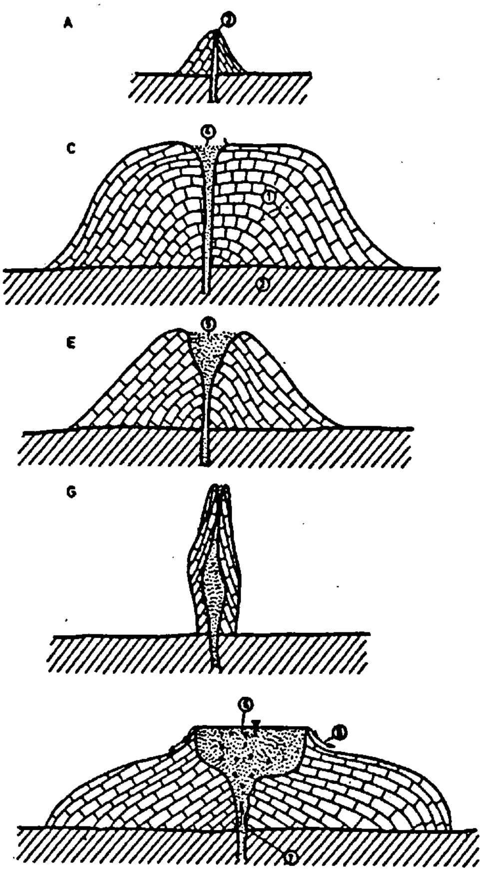


Figure 4 *Main morphological type of travertine cones.*
A = Regular small spring cone, B = Distorted small spring cone C = Elongate cone, D = Coalesced spring-cones aligned, E = Regular spring-cone, F = Spring-cone with parasitic cone, G = Spring-cone of small basal area with steep sides, H = Steppes spring-cone "Tetarata", I = Cone with spring-lake, J = Flat spring-cone of low height.
1 = Freshwater limestone, 2 = Country rock, 3 = Spring vent, 4 = Spring funnel, 5 = Spring-neck, 6 = Spring-lake, 7 = Upwelling waterflow, 8 = Overflowing springwater

8.4. The type of *tetarata barrier travertines* is genetically similar to the travertine type on hillslopes only with different geomorphological conditions, and the surfaces where travertine is precipitated are larger. In their origin flat surfaces above the level of the

Picture 2 *Impressive travertine accumulation precipitated from spring waters flowing down valley walls, Hamman Meskoutine, Algeria*

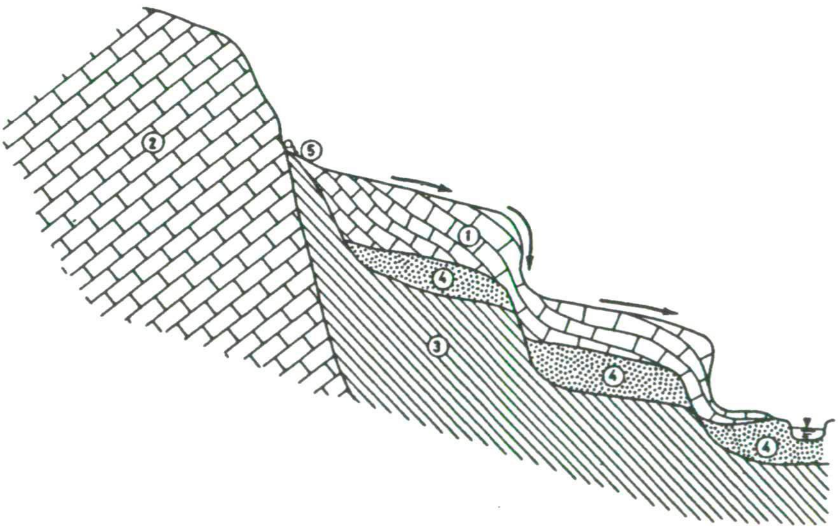


Figure 5 *Travertine of valley-side type.*
1 = travertine; 2 = water-holding limestone or dolomite; 3 = impermeable rock; fluviatile sediments, occasionally slope deposits; karst spring

Picture 3 *The valley-wall type travertine of the Pamukkale thermal spring in Turkey.*

flood-plain (broad terraces, pediments, raised beaches) can be postulated and hydrologically springs of abundant discharge can be taken into account. The karst water under considerable hydrostatic pressure mostly issues from springs in karstic horsts covered by unconsolidated deposits or directly in karst outcrops, or perhaps from springs of abundant water along faults where spring lakes form. Spring water builds a tetarata barrier on the lake margin. The spring water which issues on a higher surface flows over lower geomorphological surfaces, too, giving rise to lake basins. From the downflowing spring water tetarata barriers result in the accumulation of thick travertine series in the lake behind the barriers (*Fig. 6*).

8.5. *Travertine of mixed type.* The last described types can often intermix with each other with the changing geomorphological and hydrogeographical conditions, and one type may survive another. Thus rather diverse travertine series of mixed local properties come about.

Of all travertine types this group has the most intricate structure. This group is also considered an indicator of geomorphological surfaces.

9. The above outlined classification and the new interpretation of spring dynamics enabled, among others, *the recognition of travertine bodies formed in spring funnels and behind tetarata barriers, the correct explanation of the site of origin of travertine series of 30 to 40 m thickness and the interbedded terrestrial deposits and the better understanding of their chronological role.*

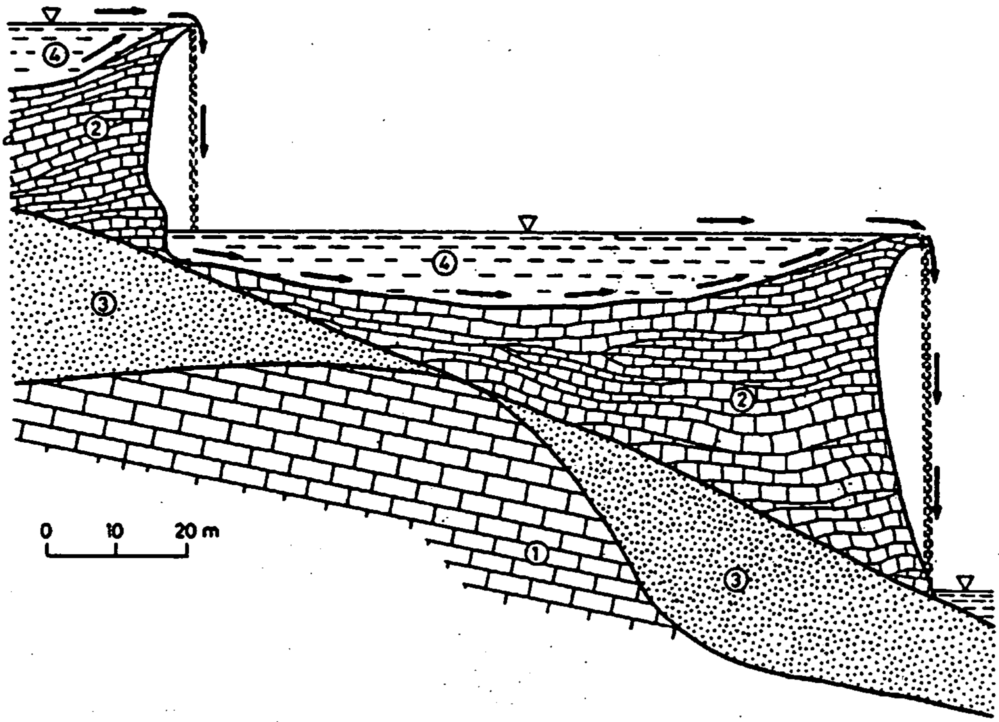


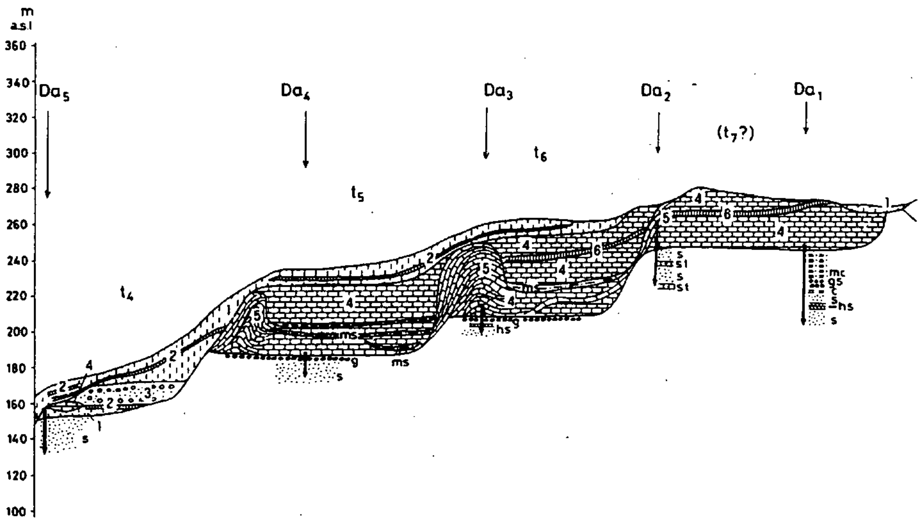
Figure 6 *Formation of tetarata basins of terraced slopes*
1 = travertine; 2 = tetarata dam; 3 = floor; 4 = tetarata lakes

The significance of travertine horizons is underlined by the fact that in the Buda and Gerecse Mountains, and generally in mountains of Mesozoic rocks, distinct geomorphological surfaces (raised beaches, pediments, terraces, etc.) are less frequent than travertine horizons on valley hillslopes. In our experience the higher terraces of valley sides (if uncovered by travertine) may be eroded or buried under slope deposits. In the mountain fore lands of unconsolidated sediments pedimentation continued in certain periods of the Pleistocene, while in the more humid interglacials intensive dissection erased even the last traces of older geomorphological surfaces, the steps of terraces.

10. Since the possibility of karst water activity resulting in travertine accumulation can be associated with as much as four or five geomorphological-karst hydrological situations, the *correlation between travertine occurrences and geomorphological surfaces* also became more intricate.

In most of the cases travertine accumulates on the basic level. The travertine formed there always *preserves a certain geomorphological surface and pointed to its evolution*.

It occurred, however, that travertine series deposited on surfaces above the base level or on hillslopes in some special situations. Some karst springs may have been active in identical topographical positions for longer periods, while in the near neighbourhood there was a remarkable change in the relative elevation of the base level (due to valley cutting or terrace formation on a lower level, etc.). The change (subsidence) of base level did not involve the sinking of the level of karst springs in each of the cases and always in a short time (*Fig. 7*).



1 = loess, slope loess; 2 = fossil soils in loess; 3 = terrace gravel; 4 = travertine;
5 = tetarata dams; 6 = fossil soil in travertine;
D_{a1}-Da5 = borehole locations; t_4-t_7 = terraces; c = clay; mc = muddy clay; ms = muddy sand; s = sand; gs = gravelly sand; hs = hydromorphous soil; st = sandstone; g = gravel.

Figure 7 *Profile of Danube terraces V-VII and the overlying travertine sequences based on superficial exposures and boreholes* (after Pécsi, Scheuer and Schweitzer, 1980).

11. On the basis of *the relationship between the base level and the displacement of springs* three cases are frequent for the travertine formation.

In the *first* possible case, the lowering of the base level is followed by the springs. The springs above the local base level cease to be active in a very short time, and thus become travertine series distinct in both age and geomorphological form. This type is mostly characteristic of the valley floor lacustrine-paludal type of travertines.

In the *second* case springs always follow the subsidence of the base level of erosion, but springs on higher levels keep up their activity or slowly run dry with gradually decreasing discharge.

Here the old spring on higher level keeps on depositing travertine, but in a reduced rate according to the decreasing discharge. The new spring issuing on the lower level begins to accumulate travertine in its environs, too. If the distance between the two springs is not so large as to allow independent lime accumulation, the processes are connected and complex intertwining travertine results. In these cases detailed investigations are necessary to establish the correct sequence of layers.

If the karst springs on the lower and higher terrain are distinct from each other spatially, independent travertine formation begins on the lower level, too.

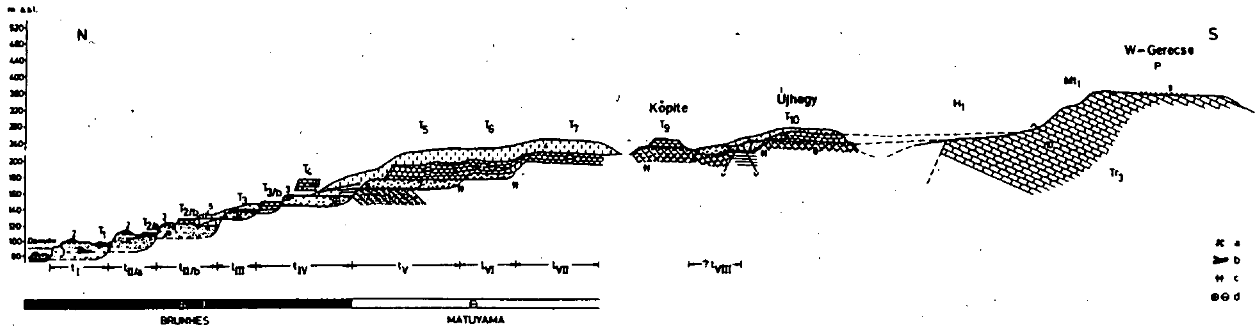
In the *third* possible case springs follow the subsidence of the local base level with a delay, or do not follow it at all. As a result on the terraced valley sides formed in several stages, mainly valley-side and mixed type travertine series formed in an intricate tetarata fashion.

12. Spring discharge and consequently assumed *travertine deposition had optimal* conditions if precipitation was abundant all through the year, and annual peaks of precipitation occurred in spring, autumn, and winter. Travertine accumulation of lesser intensity or of a temporary nature is probable if there is a more humid spell within a drier climatic period, or due to lesser evaporation and sparser vegetation the conditions for the recharge of water are less favourable under the conditions of lower values of annual precipitation.

13. The reevaluated previous and recent results in the investigations of flora, molluscs, and vertebrate fauna within the periods of the Pleistocene considered up to now homogeneous, several distinct climatic stages followed each other. The flora and mollusc investigations prove that travertines may form in any period when the necessary conditions exist (precipitation, vegetation) and therefore *their origin, contrary to the general opinion, cannot be restricted to the interglacials or interstadials*. The rate of travertine accumulation and the intervals indicate the time of the given climatic change. Thus *travertine series also reflect the climatic stages of the period of their origin*. In these investigations much help is given by the so far neglected unconsolidated sedimentaries of various types and age which reflect different climates, and are interbedded in the travertine series (such as loess, sandy loess, sand, fossil soils, deluvia, etc.).

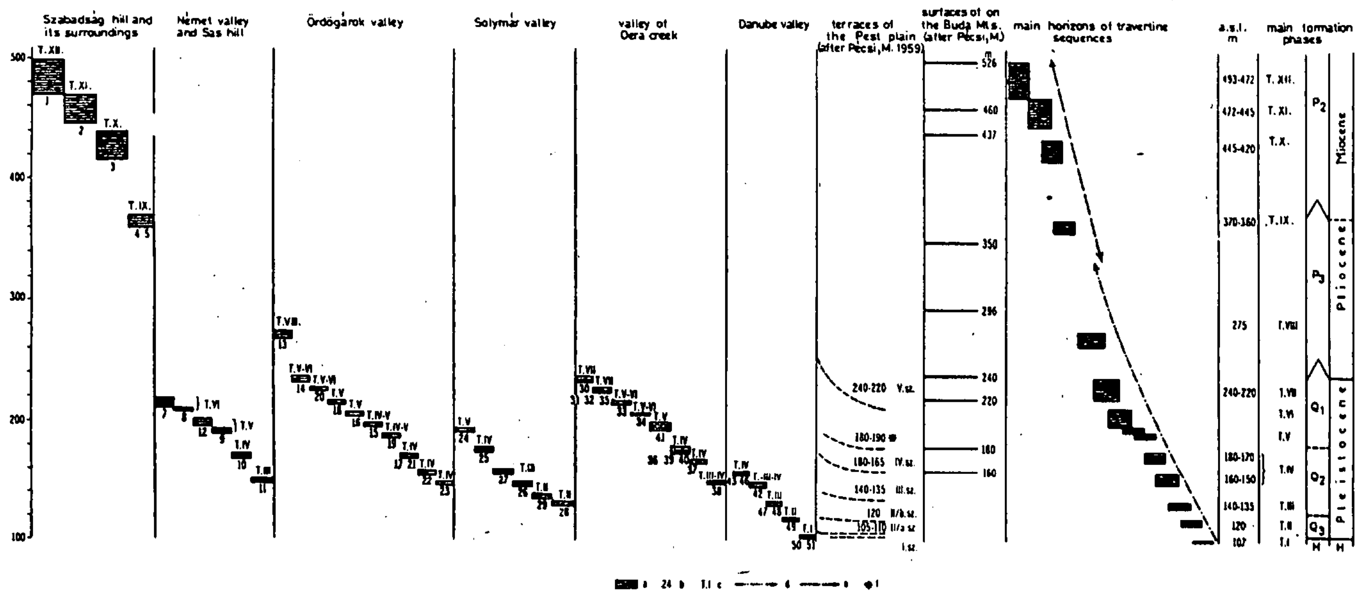
Role of Travertines

14. A peculiar geomorphological feature of the Hungarian Mountains is the frequent accentuation of the Neogene and the younger Quaternary geomorphological surfaces by occurrences of travertine overlying them. The investigations allow the conclusion that travertine series appear on at least ten geomorphological surfaces of the Gerecse Mountains, and on twelve surfaces into the Buda Mountains. Although in some groups of the Gerecse and the Buda Mountains *travertines occur in different positions, their positions also indicate a chronological sequence* (*Figs. 8, 9*).



1 = Fluviatile terrace gravel and sand; t_I-t_{VII} = terraces, Terrace gravel t_{VIII} is presumed to overlie the Upper Pannonian delta gravels by an erosional unconformity, destroying the uppermost Pannonian cross-bedded sands; 2 = blown sand; 3 = remnants of Pleistocene cryoturbation; 4 = loess, slope loess; 5 = fossil soils in loess; 6 = travertine horizons; T_1-T_{10} = travertine horizons of different age; 7 = Upper Pannonian cross-bedded sands and gravel with rounded travertine blocks in lower parts; 7a = Upper Pannonian cross-bedded sand (?) Bélbaltavárium?; 8 = Upper Pannonian clays; 9 = Miocene (?) terrestrial gravels; 10 = Upper Triassic limestone; H_1 = Upper Pliocene pediment remnant with Upper Pannonian wave-cut platform No. 2 preserved on its margin; M_{II} = Upper Pannonian marine terrace; P = pre-Tertiary — Tertiary planation surface with Miocene terrestrial gravel occurrences; a = fauna location; b = fossilized tree trunk; c = traces of hot spring tunnels in travertines and gravel; d = palaeomagnetic polarity.

Figure 8 *Geomorphological horizons of the Western Gerecse Mountains* (after Pécsi, Scheuer, Schweitzer and Pevzner).



a = travertine horizons; b = locations of occurrences; c = T_I-T_{XII} = main travertine formation phases; d = travertine horizons associated with Danube-valley occurring on the eastern margin of the Buda Mountains and formed during the development of valley systems; e = travertine horizons associated with tectonic movements (mainly uplifted) and related valley formations in the János and Szabadság-hill region; f = local terrace occurs in Pest-plain between alluvial fan terraces IV and V.

Figure 9 *Travertine horizons and main formation phases in the valleys of the Buda Mts.* (after Scheuer and Schweitzer, 1973).

Undoubtedly the oldest travertines in the Carpathian basin are related to the raised beaches of the Pannonian inland sea or to gravelly deltaic deposits, or overlie them and are also situated on Pliocene pediments.

Certain geomorphological surfaces are mostly preserved by travertines to this day.

15. It was found that most of the travertine horizons formed (on the actual base level on Pannonian raised beaches, pediments, fluvial terraces and lacustrine raised beaches) and the travertine series accumulated in this position always preserve a certain geomorphological surface and reflects its evolution.

Consequently, the places of issue of Pliocene and Quaternary karst springs regionally also followed the evolution relief of the periodical subsidence of base level from the Middle Pliocene, both on mountain margins and in the valleys. The *cessation of activity of springs* issuing on the geomorphological surfaces *were caused by* changes in the karst hydrological system (*subsidence, uplift*) which can be followed not only vertically but also horizontally (*Fig. 10*).

16. In the Carpathian basin the travertine horizons are *associated with* characteristic *geomorphological surfaces*: the horizons were formed them:

a. Pannonian (Upper Miocene) raised beaches;

b. Pliocene pediments;

c. Pleistocene terraces nos. II/a to VII;

d. Holocene surfaces.

Day spring caves can be associated with Pannonian or Pliocene erosion surfaces: they only serve to supplement correlation which represents some stages of valley development.

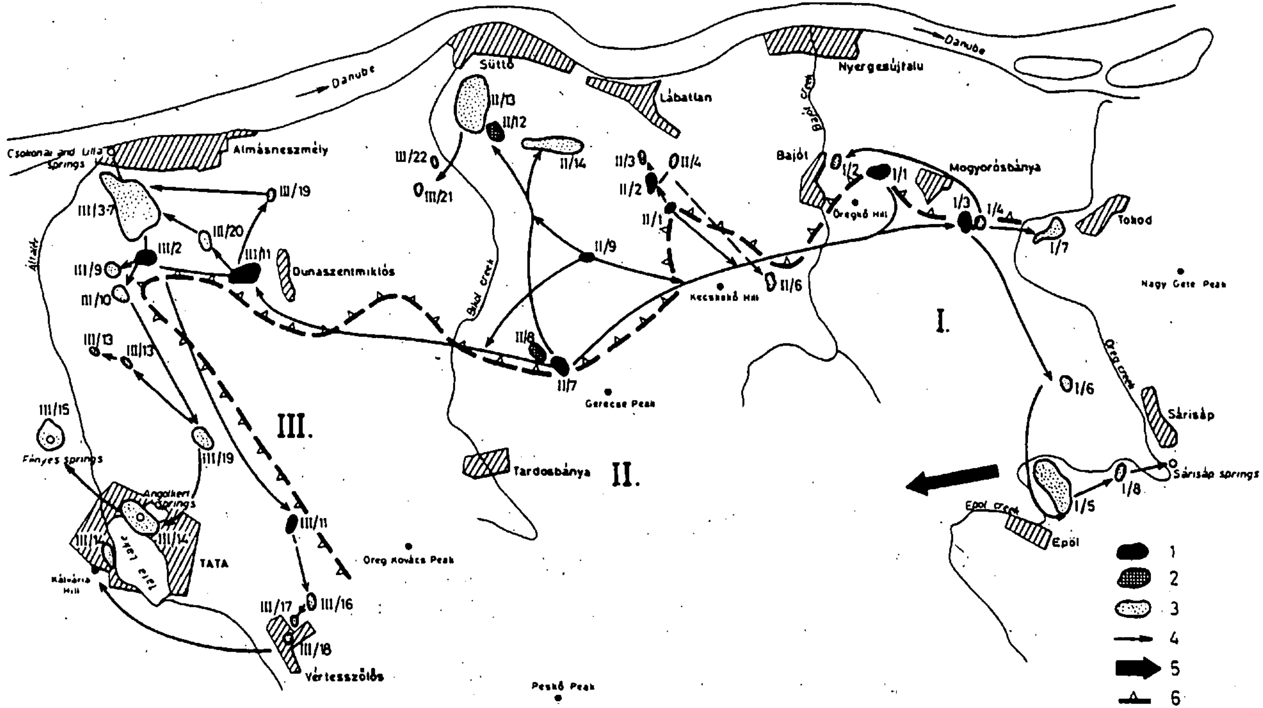
For the alteration of base levels for springs it can be hypothesized that they reflect Pliocene and Quaternary tectonic stages.

In the Buda and Gerecse Mountains travertine occurrences indicate ten to twelve geomorphological surfaces (after some simplifications) which show the degree and stages of tectonic uplift continued in cycles from the Upper Miocene (Lower Pannonian) to the Holocene. The rate of uplift — by the positions of travertine horizons — may have been 70 to 80 m in the Upper Miocene, 80 to 100 m in the Pliocene, 130 to 140 m in the Quaternary and within that value 6 to 8 m in the Holocene.

DATING OF TRAVERTINES BY GEOMORPHOLOGICAL, BIOSTRATIGRAPHICAL, PALAEOMAGNETIC, AND ABSOLUTE CHRONOLOGICAL (C^{14}, Th/U and ESR) METHODS

17. Previously by geological, geomorphological, paleontological and archaeological data and finds only classic relative dating could be used.

In the last two decades some new chronological methods evolved which enabled us to date the absolute age of travertines overlying certain terraces. In the early 1970s a team was established, led by M. KRETZOI and M. PÉCSI, to continue the geochronological evaluation of geomorphological surfaces with biostratigraphic finds. This work still goes on (HENNING, G.I. — GRÜN et al. 1983; SCHWARZ, H.P. — SKOFLEK, I. 1982).



1 = Upper Pannonian springs and travertines; 2 = Upper Pliocene springs and travertines; 3 = Quaternary springs and travertines; 4 = direction of spring displacement; 5 = direction of Late Pleistocene spring displacement; 6 = <R>presumed Upper Pannonian shoreline; I = Eastern Gerecse; II = Central Gerecse; III = Western Gerecse.

Figure 10 *Principal travertine occurrences in the Gerecse Mountains* (after Scheuer and Schweitzer)

To establish age units of travertines and *to place* their geomorphological positions *on a time scale* the Upper Cenozoic stratigraphic-morphogenetic-climatic and biological evolution synthesis, the Pliocene-Quaternary chronostratigraphic system by M. Kretzoi (1969), D. Jánossy (1978), M. Pécsi (1970), and M. Kretzoi and M. Pécsi (1979) was used as a basis (*Tables 1-2*).

18. On the fluvial terraces, pediments and raised beaches on the margins of the Gerecse and Buda Mountains ten or twelve travertine horizons of various ages are located in a step-like fashion. They help to reconstruct a splendid series of events, *stages of tectonic movements* during the Pliocene and Quaternary relief evolution.

19. *Ordinals* were placed to the travertine occurrences from the lowest-lying one (at 107-100 m a.s.l.) to the highest one (in the Buda Mountains at 493 m a.s.l., in the Gerecse Mountains at 350 m a.s.l.) and they were given *signs from T_1* to T_{12}. Two groups can be differentiated for the travertine horizons arranged in a step-like fashion.

a. The members of the *lower series* — deposited on terraces on the valley sides — come close above each other between 107 and 250 m a.s.l. (horizons T_1 to T_7).

b. The members of the *higher series* (T_8 to T_{12}) — deposited on older geomorphological surfaces — follow each other with considerable intervals of height and, compared to the lower ones, they manifest distinct lithological differences, too.

20. In the *Gerecse Mountains* the members of the lower series can be correlated to the Danubian terraces (*Fig. 8*).

20.1. *Travertine T_1* was deposited on the high flood-plain (*Terrace I/b*). The age of the tree trunk find of the terrace gravel was found 11,830 ± 10000 years old, i.e., early Holocene, by C^{14} examination.

20.2. *Travertine T_2* covers the second flood-free terrace (*no. II/b*). At Tata the age of the lower part of the travertine deposited on the terrace II/b of the Általér stream, and including the paleolith settlement, is 101,000 ± 10,000 years, and the age of the upper part is 98,000 ± 8,000 years. In the Vértesszőlős section its Th/U age is 135,000 ± 11,000 years. The travertine can be dated in the last interglacial (Pict. 4).

20.3. *Travertine T_3* overlies the Általér terrace III. At Vértesszőlős it is 248,000 ± 67,000 years old. The ESR age of this latter is 202,000 ± 20,000 years. The travertine belongs to *the middle part of Solymár period.*

20.4. *Travertine T_4* overlies terrace IV. Its ESR age at Dunaalmás is 360,000 ± 36,000 years and in the Vértesszőlős section the one containing the paleolith settlement is more than 350,000 Th/U years. *According to the faunistic finds it can be referred to the Tarkő period of the Upper Biharian.*

20.5. *Travertine T_5* is paleomagnetically of reverse polarity, i.e. older than 700,000 years. In the new interpretation of the Archidiskodon meridionalis (planifrons) FALC, Megaloceros sp. and accompanying faunas (KRETZOI, M. 1954, 1979; JÁNOSSY, D. 1979) Lower Pleistocene—Lower Biharian age is postulated.

20.6. *Travertine T_6* also shows reverse polarity and was formed in the Matuyama palaeomagnetic era reaching back to 2.4 million years. By the rich microfauna of the red brown paleosol interbedded into travertine layers it can be referred to the *Kisláng horizon of the Upper Villányium* (JÁNOSSY, D. 1979).

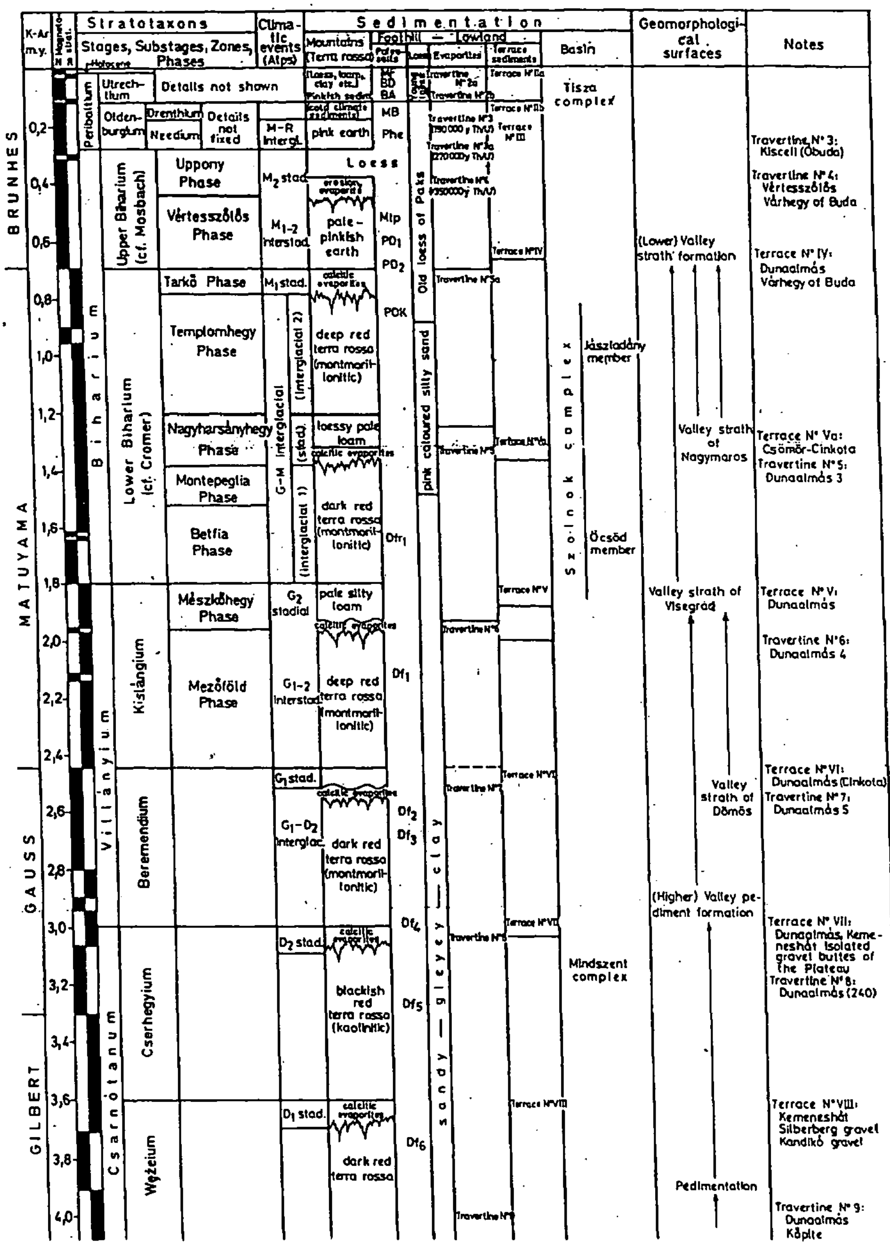


Table 1. *Correlation of the Terrestrial, Biostratigraphical and Geomorphological History of the Pliocene and Quaternary in the Carpathian Basin* (Kretzoi and Pécsi).

m.y.	Stratotaxons: Stages	Substages, Zones		Sedimentation: Travertines	Terraces	Basin sediments	Tectonics	Geomorphological surfaces	Notes
	Peribaltium	Utrechtium Oldenburgium	—	For details see Table 2					
	Biharium	Uppony Vértesszőlős		Travertine N°4 Travertine N°5a	Terrace N°IV				
1		Lower Biharium (cf. Cromerium): Tarkő Templom-hegy Nagyharsány-hegy Montepeglia Betfia	OM.1	Travertine N°5	Terrace N°Va		Bakinian (2-300 m upheaval)		
2	Villányium	Kislángium	NM.17	Travertine N°6	Terrace N°V				
		Beremendium	NM.16	Travertine N°7	Terrace N°VI		Villányian		
3	Csarnótanum	Cserhegyium	NM.15	Travertine N°8	Terrace N°VII		Basalt tuff ? ?New Roumanian	Pediment surfaces N° 2a	Basalt tuff: Magyargencs
4		Wężelum			Terrace N°VIII				
5	Ruscinium		NM.14	Travertine N°9	Old gravel sheet		? Roumanian	Pediment surface N°1	Kandikó, Silberberg (Ezüst-hegy)
6		Estramontium				Terrestrial sedimentation Cross-bedded fluviolacustrine sand group	Rhodanian	Beginning of the main period of pedimentation	
7	Baltavárium	Bérbaltavárium	NM.13	Travertine N°10a	Beginning of river system forming				T.N°10a. Gerecse: Mogyorós-bánya; Kőhegy; Várpalota
		Hatvanium					Basalt N°3		Basalt N°3 Pula; Gérce
8		Sümegium	NM.12	Travertine N°10	Marine terrace N°1		Basalt N°2		T.N° 10. Várpalota; Nagyvázsony; Széchenyi-hegy; Gerecse: Új-hegy (320);
9 10		Csákvárium	NM.11	Travertine N°11	Marine terrace N°2a	Late Pannonian sand-silt-clay group	Basalt N°1 Attican II		Mt.N°2a. Gerecse: Margithegy; Vértes: Haraszthegy; K.Bakony: Várpalota T.N°11. Szabadsághegy (499–472); D.Bakony: Kapolcs
11		Rhenohassium	NM.10		Marine terrace N°2 Delta gravel formation				Mt.N°2. Bakony: Bakonynána; Vértes: Murva-domb; Gerecse: Dunaszentmiklós (delta gravel)
12	Eppelsheimium	Bodvaium	NM.9			Early Pannonian shale group			
13		Monacium	NM.8		Marine terrace N°3	Glass sand Ground gravel group			Mt.N°3. Budai-h.: Diósd-Sóskút; Balatonfelvidék: Balatonfüred

Table 2. *Correlation of the Terrestrial, Biostratigraphical and Geomorphological History of the Upper Pliocene and Quaternary in the Carpathian Basin* (Kretzoi and Pécsi).

Picture 4 *Travertine cone with spring funnel. In the background a small parasitic cone is seen. Vysny Sl.ac, Slovakia*

20.7. *Travertine T_7* shows red clay accumulations in its karstic depressions. At Süttő the Tapirus sp. find found in the Harasztihegy travertine and the archaic shape of the Archidiskodok meridionalis (JÁNOSSY, D. 1979) indicate upper *Csarnotanum, Cserhegyium*.

20.8. *Travertine T_8* can be referred to the upper horizon of the Upper Pannonian (Bélbaltavár period) identified by the enclosed mollusc fauna, and by the Unio wetzleri horizon.

20.9. *Travertine T_9* and T_{10} are the highest occurrences in the Gerecse Mountains (300 to 340 m a.s.l.). They are deposited on Upper Pannonian sandy-gravelly delta sediments and raised beaches. Their date of origin can only be estimated in lack of direct information. In the travertine T_9 — deposited at 300 m a.s.l. — Rozlozsnik (1919) recognized Upper Pannonian Dreissena sp. This is one of the most important evidences that the geomorphological surfaces mantled by travertine horizons at 300-340 m a.s.l. belong to the Upper Pannonian. By the position of travertines, they belong to the terrestrial *Upper Pannonian Sümegium* or to the *lower Upper Pannonian*.

21. *In the Buda Mountains* — similar to the travertine horizons in the Gerecse Mountains — the members of the lower seies (T_1-T_7) could be corresponded to the terraces of the Danube and its tributaries (*Fig. 9*).

21.1. *Travertine* T_1 is deposited on the high flood-plain (on terrace I/b) at 105-108 m a.s.l. The radiocarbon analysis of the paleosol dividing the blown-sand series covering the terrace II/a of the Pest Plain is of Early Holocene age (9,500 years).

21.2. *Travertine* T_2 covers terrace II/b (120 m a.s.l.). Its Th/U age is 70,000 years.

21.3. *Travertine* T_3 accumulated on the Danube terrace III (150 m a.s.l.). By Th/U analyses it is dated at 175,000 years and can be corresponded to the middle part of the *Solymár period*.

21.4. *Travertine* T_4 is deposited at 170 to 180 m a.s.l. and adjusts to the Danubian terrace IV. According to palaeomagnetic analysis it has normal polarity. The Th/U age of the travertine overlying terrace IV is 358,000 years. Faunistic finds also give evidence to the Tarkő period of the Upper Biharian (JÁNOSSY, D. 1979).

21.5. *Travertines* T_5 - T_6 lie at 220 to 200 m a.s.l. They have reverse polarity, i.e. they may be older than 700,000 years. The enclosed fauna remnants — Archidiskodon "Trogontherii Cromerensis Depéret et Majet", Mimomys savini Hinton, Hippopotamus antiquus Desmarest etc. — indicate Lower Biharian (JÁNOSSY, D. 1978; Pict. 1).

21.6. *Travertines* T_7—T_8 are deposited on pediments of the Szabadsághegy — the higher at 360 to 370 m a.s.l. and the lower at 270 to 250 m a.s.l. Chronologicallly significant fauna have been revealed from them.

21.7. *The older travertine horizons* (T_9—T_{12}) are deposited on Upper Pannonian sandy-gravelly deltaic deposits and on raised beaches. Their dating had been uncertain until recent years. They were generally considered Levantan or Lower Pleistocene. The most recent geomorphological and paleontological investigations help divide the travertine series regarded homogeneous up to now.

The *oldest travertine* T_{12} (472-499 m a.s.l.) overlies the *Eppelsheimian (Lower Pannonian)* raised beach by its geomorphological position.

The lower-lying T_{11} travertine horizon M (472-445 m a.s.l.) is underlain by Lower Pannonian according to M. Kretzoi (1981) judged from the collected Aceratherium incisivum KAUP, sp. fauna. Thus the age of the distinct travertine horizon at 472-499 m a.s.l. one level higher, is either Csákvárium or the older *upper part of the Lower Pannonian*, the *Rhenohassium*.

Travertine T_{10} also overlies the raised beach of the Széchenyi-hegy. The fauna identified by M. Kretzoi (1978) from the travertine at 420 m proves *Sümegian age*. This travertine is distinct in position and lies about 80 m lower than T_{12}—T_{11} horizons on the Szabadság-hegy. According to M. Kretzoi its Parapodemus, Gerbillida and Ochatonida sp. exclude the possibility of Lower Pannonian (Eppelsheimian) age and the small Giroffida and Tapiriscus give testimony against Upper Pannoniaum (Hatvanium or Unio wetzleri).

POSSIBLE INDUSTRIAL USE OF TRAVERTINE SERIES WITH SPECIAL REGARD TO RESEARCH IN TO ORNAMENTAL STONES

22. The extended *application* of travertines *in building industry* is common and popular. Therefore, the quantitative and qualitative cadastral survey and reserves calculations for the building-industrial use of travertines has begun.

In Hungary, the rapid and dynamic urban development of the last decades increased the demand for building raw materials, and it motivates and necessitates the survey of the available reserves in order to promote their rational exploitation and utilization.

REFERENCES

Allen, E.T. and Day, A.L., Hot springs of the Yellowstone National Park, Carnegie Institution of Washington Publication 446, 525 p. (1935)

American Geological Institute, Dictionary of geological terms, Olphin Reference Book, p. 360. (1962)

Burnes, Iván and O'Neill, J.R., Calcium-magnesium carbonate solid solutions from Holocene conglomerate cements and travertines in the Coast Range of California, Geochimica et Cosmochimica Acta, V. 35, pp. 699-718. (1971)

Baszkov, E.A. and Szuzikov, Sz.N., Gidrotermál Tyihookeanszkogo szegmenta zjemli, Moscow, p. 171. (1975)

Bögli, A., Karsthydrographie und physische Speläologie, Springer Verlag, Berlin-New York, pp. 1-137. (1978)

Evans, P., The Present Status of the Determination in the Quaternary (with Special Reference to the Period between 70,000 and 1,000,000 Years ago), 24th IGS, Section 12, Quaternary Geology, Montreal, pp. 16-21. (1972)

Feth, J.H. and Barnes, I., Springs Deposited Travertine in eleven Western States, U.S. Department of the Interior Geological Survey, pp. 1-68. (1979)

Frechen, J. and Lippolt, H.J., Kalium-Argon-Daten zum Alter des Laacher Vulkanismus, Eiszeitalter und Gegenwart, 10., pp. 5-30. (1965)

Geurts, M.A., Genese et Stratigraphie des Travertins de Fond de Vallée en Belgique, Acta Geographica-Lovaniensie, 16, pp. 1-66. (1976)

Hennig, G.J., Grün, R., Pécsi, M. and Brunnacker, K., Th-230/U-234 — sowie ESR-Altersbestimmungen einiger Travertine in Ungarn, Eiszeitalter und Gegenwart, 33, pp. 9-19. (1983)

Jánossy, D., A magyarországi pleisztocén tagolása gerinces faunák alapján (Classification of the Hungarian Pleistocene based on vertebrate fauna), Bp. Akad. K., 206 p. (1979)

Jakucs, L. Aggtelek és környéke (az észak-borsodi karsztvidék) útikalauza. Bp. Sport. 358 p. (1961.)

Jakucs, L. A karsztok morfogenetikája. A karsztfejlődés varianciája. Bp. Akad. K. 310 p. (Földrajzi Monográfiák 8.) (1971.)

Jakucs, L. Szerelmetes barlagjaim Bp. Akad. K. 315p. (1993.)
Lozek, V., Travertines, INQUA, Warszawa. pp. 1-19. (1961)
Messini, M. and di Lollo, E.C., Acque minerali del mondo, Roma, 417 p. (1957)
Pécsi, M., Hegylábi (pediment) felszínek a magyarországi középhegységekben (Pediment surface in the Hungarian Middle Mountains), Földr. Közlem. 11, 3, pp. 195-212. (1963)
Pécsi, M., Development of the Hungarian section of the Danube valley, Geoforum, 6, pp. 21-32. (1971)
Pécsi, M., Geomorphological position and absolute age of the lower Paleolithic site at Vértesszőlős, Hungary, Földr. Közlem. 21, 2, pp. 109-119. (1973)
Pécsi, M. and Osmond, J.K., Geomorphological position and absolute age of the settlement at Vértesszőlős of the lower Paleolithic prehistoric man in Hungary, Ninth Congress Internat. Union Quaternary Research, Christchurch (N.Z.), 2-10 Dec. 1973, Abstracts, pp. 283-284. (1973)
Pécsi, M., Scheuer, Gy. and Schweitzer, F., Die plio-pleistozänen tektonischen Bewegungsphasen im Budaer Gebirge, DEUQUA-Tagung, 3-5 Sept. 1978, Wiener Becken — Mittleres Burgenland — Transdanubien: Excursionsführer, Helga Schneiderbauer, Budapest-Wien, pp. 45-49. (1978)
Scheuer, Gy. and Schweitzer, F., Új szempontok az édesvízi mészkőösszletek képződéséhez (New aspects on the formation of travertine sequences), Földr. Ért. 19, 1, pp. 381-392. (1970)
Scheuer, Gy. and Schweitzer, F., New aspects on the formation of the freshwater limestone series in the environs of the Buda Mountains, Földr. Ért. 33, 2, pp. 113-135. (1974)
Scheuer, Gy. and Schweitzer, F., The development of the Hungarian travertine sequence during the Quaternary, Földr. Közlem. 21, 2, pp. 133-141. (1974)
Scheuer, Gy. and Schweitzer, F., A budai hévízforrások fejlődéstörténete a felsőpannontól napjainkig (Entwicklungsgeschichte der Budaer Thermalquellen vom oberen Pannon bis zu unseren Tagen), Hidrológiai Közl. 11, pp. 492-501. (1980)
Scheuer, Gy. and Schweitzer, F., A Gerecse-hegység paleokarszthidrológiai viszonyainak rekonstrukciója a felsőpannontól napjainkig (Rekonstruktion der paläokarsthydrologischen Verhältnisse des Gerecse-Gebirge vom oberen Pannon bis zu unseren Tagen) Hidrológiai Közl. 61, 8, pp. 333-380. (1981)
Scheuer, Gy. and Schweitzer, F., A magyarországi édesvízi mészkőösszletek származása és összehasonlító vizsgálatuk (Origin of Hungarian freshwater limestone sequences and their comparative study), Földtani Közl. 111, pp. 67-97. (1981)
Scheuer, Gy. and Schweitzer, F., A Gerecse és a Budai-hegység édesvízi mészkőösszletei és képződésüknek geomorfológiai és geokronológiai sajátosságai (Travertine sequences in the Gerecse and Buda Mountains: geomorphological and geochronological features of their development). Tézisek 24—25 old. (34, 53, 61, 67. tételek). Hung. Acad. Sci., Budapest, 213 p. (1983)

Scheuer, Gy. and Schweitzer, F., The role of travertines in the geomorphological, paleohydrogeological and geochronological research of the upper Cainozoic. In: Pollution and water resoures. (Columbia University Seminar series XVII—XIX.). New-York. 71—90. (1986)

Scheuer, Gy. and Schweitzer, F., Genetics and occurrence of Holocene travertines in Hungary. In: Geomorphological and geoecological essays. (Studies in geography in Hungary 25.) Bp. Akad. K. 39—48. (1989)

Scheuer, Gy. and Schweitzer, F., Travertine formation of the Gerecse Mountains. In: Vértesszőlős site, man and culture. Bp. Akad. K. 43—62. (1990)

Schréter, A., A Buda és Gerecse hegységperemi édesvizi mészkőelőfordulások (Freshwater limestone occurrences on the margins of the Buda and Gerecse Mountains), MÁFI Évi Jel. 1953-ról, pp. 111-146. (1953)

Schwartz, H.P. and Skoflek, I., New dates for the Tata, Hungary, archaeological site. Nature, 295, pp. 590-591. (1982)

Schweitzer, F. and Scheuer, Gy., Geomorphological position and chronological classification of Hungarian travertines. In: Proceedings of the International Symposium "Geomorphology and Sea" and the Meeting of the Geomorphological Commission of the Carpatho-Balcan Countries Mali Losinj, September 22—26 1992. Zagreb, Dept. of Gejogr. Faculty of Science Univ. of Zagreb. 223—240. (1992)

Schweitzer, F., Angaben zum Trocken-warmen Klima des Ungarischen beckens Aufgrunden des "Wüstenlacks" in Mogyoród. In: Abstracts. Debrecen. Carpatho-Balcan Geomorphological Commission. 21—22. (1994)

Steiner, W., Zur Stratigraphie des Oberen Travertine im Quartär Profil von Ehringsdorf bei Weimar, Zeitschrift für geologische Wissenschaften 1, pp. 515-529. (1973)

Steiner, W., Die Faziesanalyse in der Travertinforschung, Zeitschrift für geologische Wissenschaften 7, o, pp. 443-446. (1979)

Zötl, J.G., Karsthydrogeologie, Springer Verlag, Wien-New York. (1974)

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MEASUREMENT OF KARSTIC INFILTRATION IN THE AGGTELEK KARST

László Zámbó

The percolation of precipitation into the karstic aquifer is one of the determining elements in karstification. This elements is called as karstic infiltration.

A monitoring system has been installed in the Aggtelek Karst in Hungary to study the process of karstic infiltration. This system is equipped with sensors and loggers and can continuously measure the parameters of the infiltration from the surface to the karstwater table.

The measuring station is in the Aggtelek National Park, which is a karst upland characterised by karren, dolines and river caves. Dolines and sinkholes are diagnostic features of karst terrain. They are topographically closed depressions with forms that may range from shaft through funnel to shallow water. Diameters range from less than ten to a little more than one thousand metres depth diameter ratios are normally between 1:2 and 1:20. Processes of mechanical collapse, of subsidence or suffusion may contribute to their formation but in true karst (as opposed to pseudo-karst) aqueous dissolution of the bedrock is either the principal process or it is the essential trigger for operation of any of the others.

In forest or grassland regions dissolution dolines typically are mantled with soil. There is often some outcropping of bedrock displaying karren forms on the steeper sideslopes, and a marked increase of soil thickness in the bottoms.

The study site is a rolling upland karst that straddles the Hungarian-Slovak border. Elevation ranges from 200 to 600 metres. Bedrocks are thick to massively bedded platform limestone and dolomites of Triassic age. Insoluble residuals are only 0.1 to 0.35%. There was quite intensive karstification during the Cretaceous, after which the strata were buried by Pannonian sands and clays (Miocene). They were lifted up as a horst block in Pliocene, when the modern period of erosion began. They display dense tectonic fracturing. In combination with the paleokarstification this has resulted in an unusually high density of final fissures that are penetrable by groundwaters.

Soils developed on the carbonate rocks are terra rossas and rendzinas (red to red-brown chromic luvisols and rendols in the terminology of the Seventh Approximation, 1960). They have an effective porosity of 30-50%. On slopes they are generally mixed and reworked to form a complex mosaic of relict and modern components.

The comprehensive instrumentation had to be limited to one site. This is a nearly circular feature 150 m in diameter and 12 m in depth. Its basal fill of soil is a further 7.5 metres in depth. The doline is situated over Béke Cave, which is 37 metres beneath it. There are now four measuring stations or experiments operating in the doline, plus a further one in the cave below.

The units of the measuring system are located in karstic vadose and epiphreatic zones along a vertical section. The first unit (which measures precipitation) is over the surface, the second unit (which measures run-off) is on the surface. Then follow five seepage measuring units in the thick soil accumulation at 0.5, 2.5, 5.0 and 8.5 metres. Finally, two units (Instrument No. 2 and 3) measure the infiltrating water of the ceiling of the Béke Cave, directly at the level of the karstic water table.

The following conclusions on the process of infiltration are based on a 3911 hour period between February and July 1995 (Figure 1), namely on a rainy section of this period (Figure 2).

1. Until the humidity of the top 5 cm soil layer is below 92-93%, and the infiltration capacity is higher than the precipitation, all rainwater infiltrates. At 92-93 humidity value run-off starts.

2. Infiltration in forested areas is 1-12 hours later than in grasslands.

3. The downward velocity of the infiltration front depends on the preliminary water saturation of the soil.

(i) At 0.5 m, infiltration can even be 44 hours later than the start of rainfall, depending on the humidity of the soil (Figures 4-5).

(ii) Over forested lands generally 12 hours, on open fields generally 3 hours are needed after the start of raining until the infiltration front arrives at 0.5 metres. In the case of recurring minor precipitation (4-5 mm) the infiltration front normally arrives at 0.5 m in 24 hours.

4. At medium humidity (40-50%), the infiltration reaches from 0.5m to 2.5 m after 15 hours, and usually needs another 17 hours to arrive at 7.5 m. ,

In humid soil (over 87%) the intensity of infiltration suddenly increases and synchronously changes with the surface swallowing.

5. Going downwards, the intensity of infiltration decreases and the process becomes longer in time. The infiltration follows the precipitation

(i) 4-50 hours later at 2.5 m (Figure 6), and

(ii) 7-14 days later at 5 m.

6. On slopes, at the border of decayed materials and the karstic rock, usually one hour is needed after the precipitation until the start of border surface infiltration. The velocity may be several times higher than that of the capillary infiltration. (Figure 8)

7. On karstlands which are mantled with thick (5-10 m) decayed material, at 36 m depth, the infiltration is normally 5-6 days late, while where the land is covered with thin (0.5 m) soil, it is , usually 2-2.5 days late (Figures 2-10).

8. The infiltration process becomes more and more balanced as the depth is

growing, but certain rhythmical changes in the intensity can be observed up to the karstic water table.

Changes, occasionally periodicity, in the intensity of seepage at various depths can be most easily explained by lunisolar effects, which have already been proved for movements in karstic hollows. The existence of these effects can only be presumed due to the special hydraulic rules that direct infiltration, although the mathematical analyses seem to support this.

Studying the infiltration processes at 2.5 m (Figure 11), the range of the amplitude indicated the existence of the given harmonic factor. The time period of 514 hours starting at 12 o' clock on 11 March 1995 produced 1029 data, which were analyzed by Furier transformation. With the help of this analysis it was possible to show some long periods (21, 10.5, 6.1, 3.8, 2.7, 2.12 and 1.6 days) and several short periods (Figures 12-13). A more complete explanation still needs a bigger data base and further analysis.

Measured data of karstic infiltration gave the opportunity of calculating the average value of limestone solution. On the basis of analysis carried out until now the following can be concluded.

Infiltrating water - due to lime solution - loses a part of its solution capacity in the soil cover (fixed CO_2), by solving 8.918 g/m²/year limestone. The aggressivity of the remaining part of infiltrating water is able to solve 12.71 g/m²/year limestone. The value of complete average limestone solution capacity - calculated to limestone denudation - is 0.01065 mm/year or (appr. 10 mm/thousand years.)

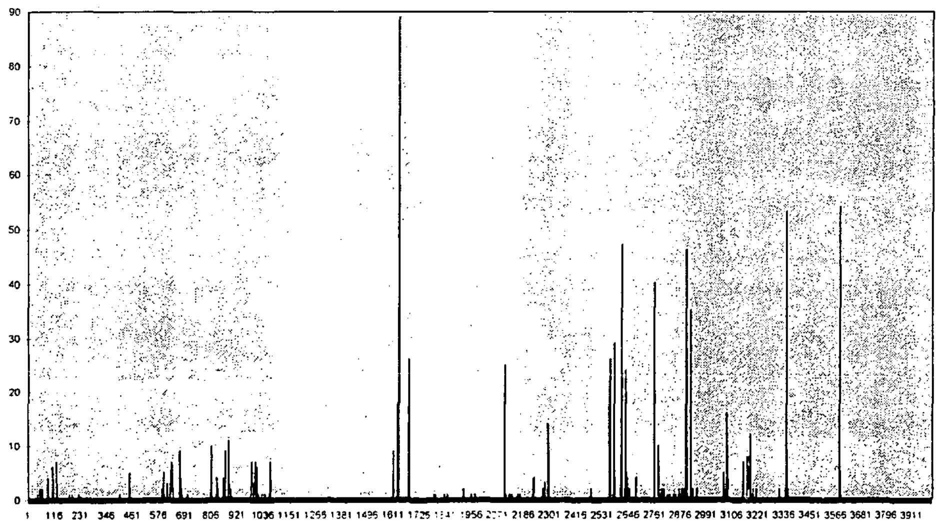

Figure 1

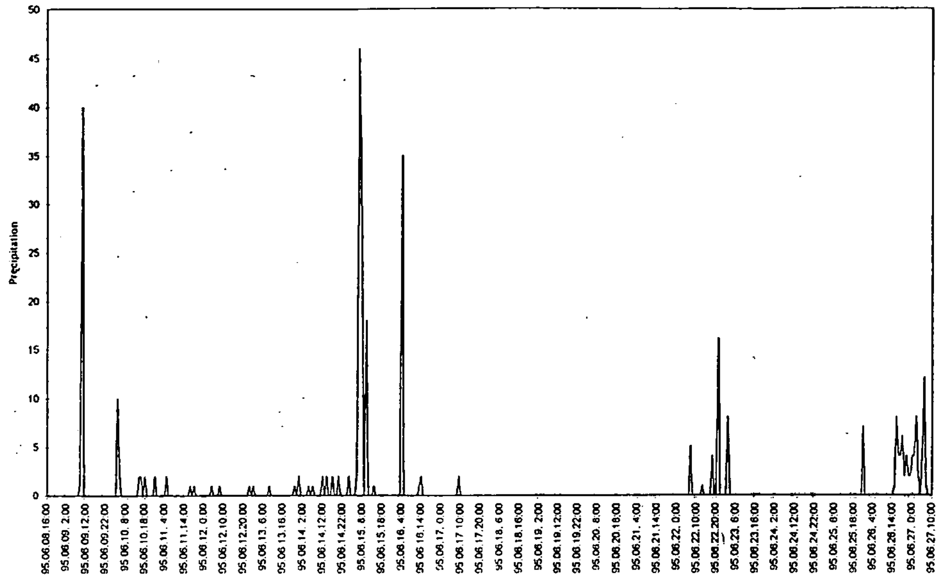

Figure 2

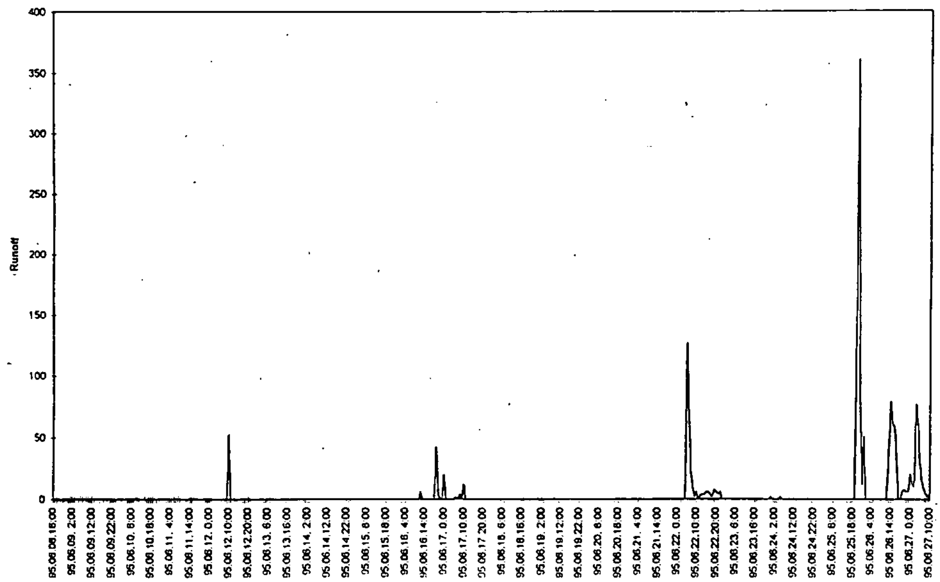

Figure 3

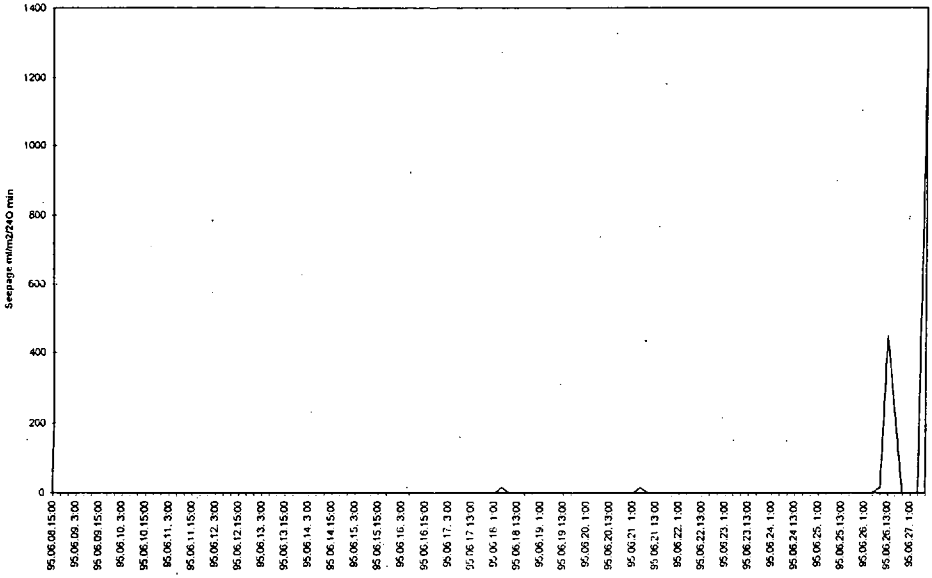

Figure 4

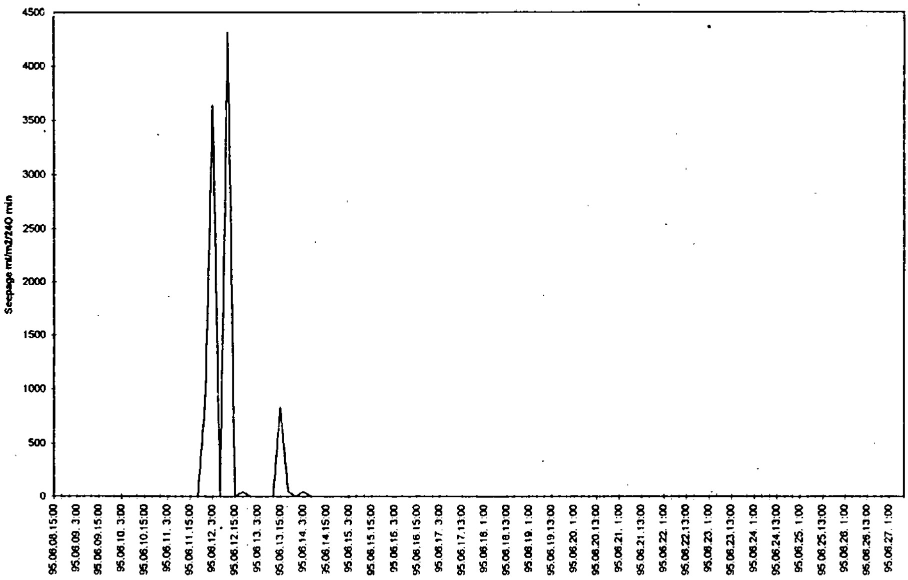

Figure 5

Unit 2

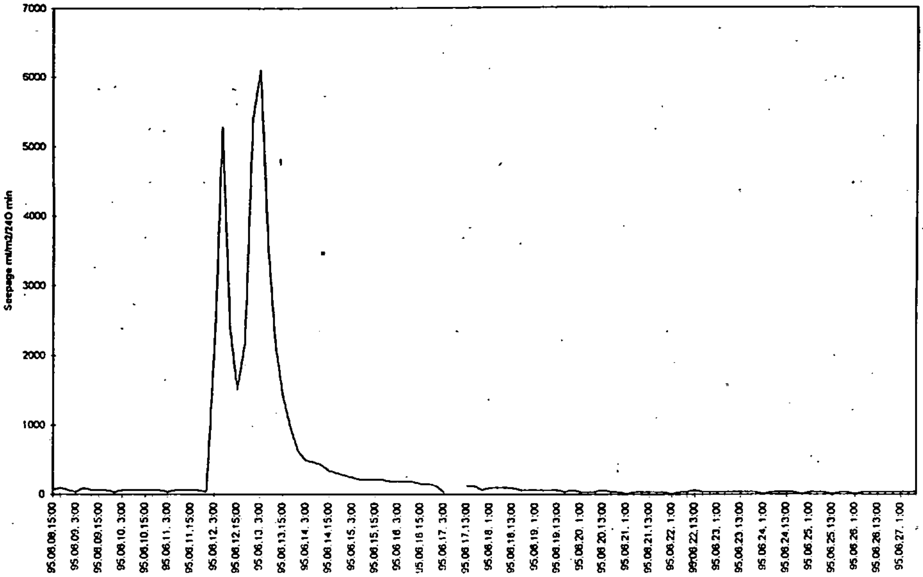

Figure 6

Unit 3

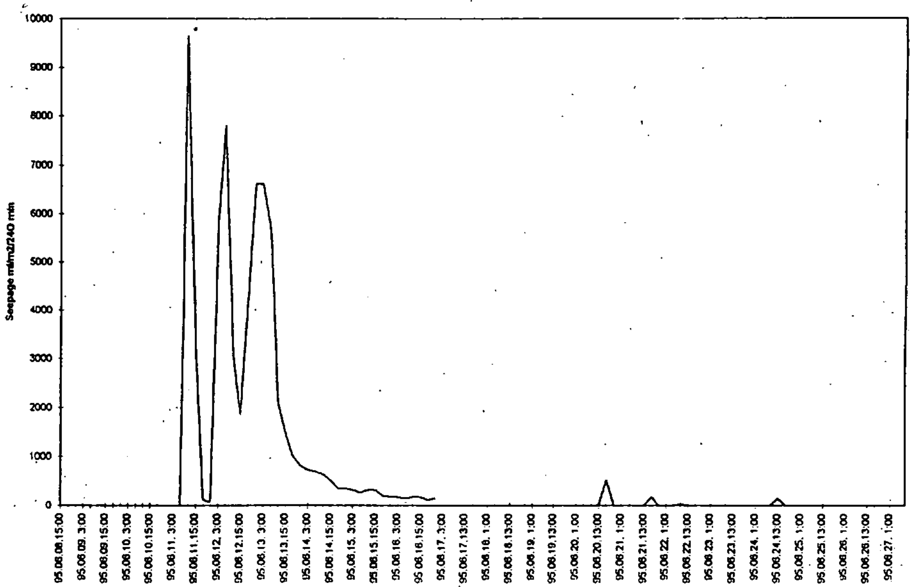

Figure 7

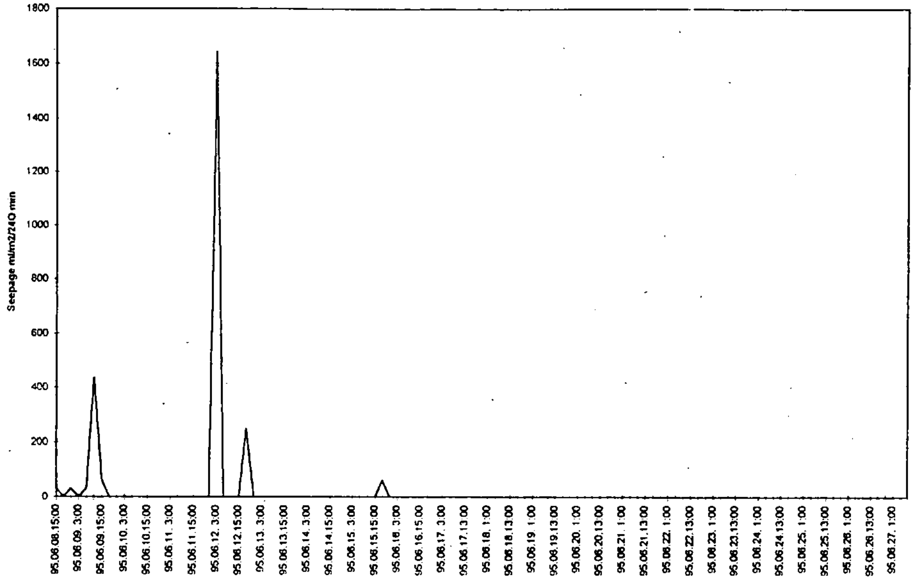

Figure 8

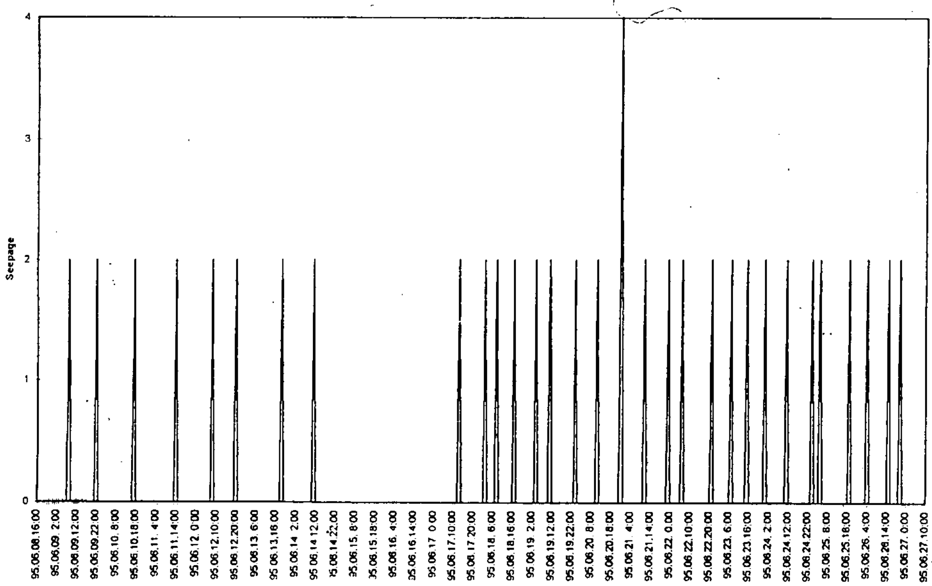

Figure 9

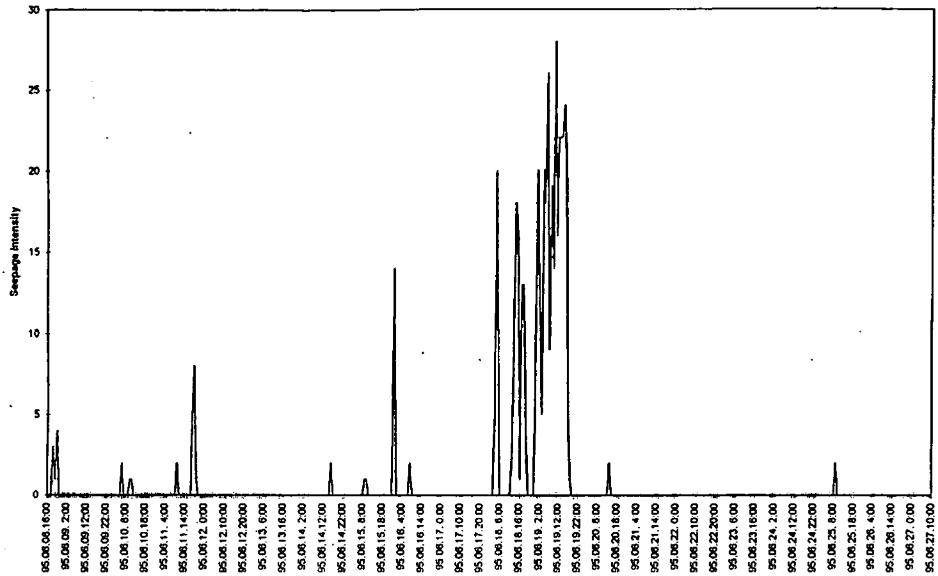

Figure 10

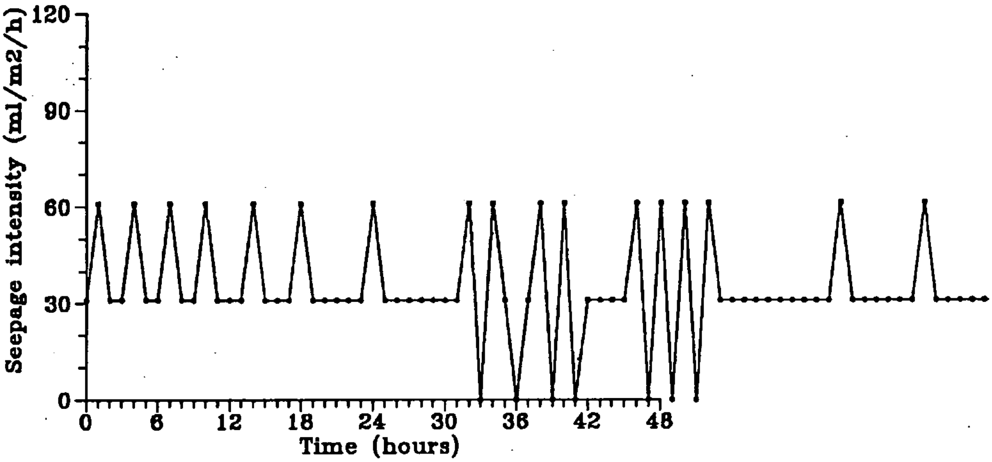

Figure 11

Amplitude spectrum

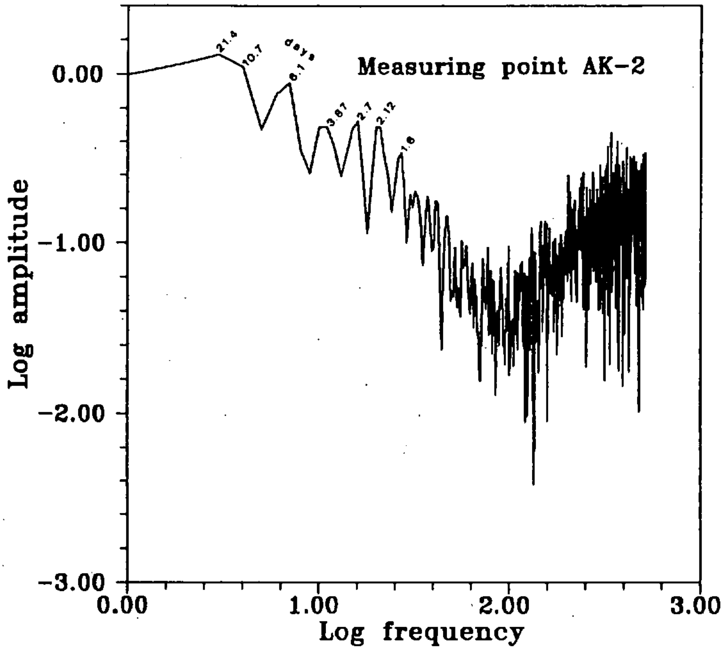

Figure 12

Power spectrum

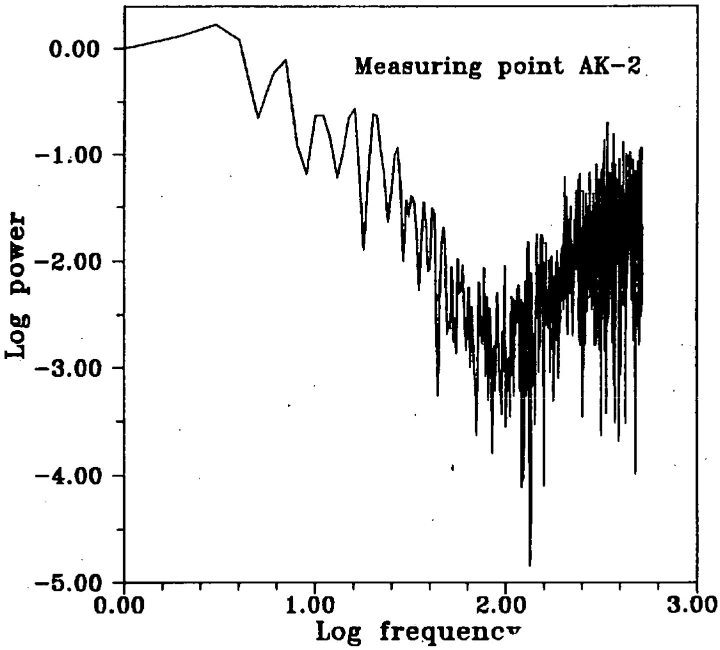

Figure 13

REFERENCES

FORD, D.C. - WILLIAMS, P.V., 1989: Karst Geomorphology and Hydrology. London, pp. 1-600.

MAUCHA, L., 1977: Study of tidal movement of karst waters and karstic rocks. Annales Geophys., Tom. 33, Fasc. 1/2. Grenoble, pp. 151-156.

WHITE, W.B., 1988: Geomorphology and Hydrology of Karst Terrains. Oxford, pp. 1-464.

ZÁMBÓ, L., 1993: Karsztmorfológia (In: Borsy, Z.. Általános természetföldrajz), Budapest, pp. 544-593.

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LIST OF PUBLICATIONS OF JAKUCS LÁSZLÓ

BOOKS:

Fenton, Caroll Lane: Földünk titkai. (Earth's adventures.) Ford. Bogsch László. Bev. JAKUCS L. Bp. [1949], Dante. 152 l. 8 t.

JAKUCS L.: Aggteleki cseppkőbarlang. [Bp.] 1952, Művelt Nép. 118 p. 1 t.

JAKUCS L.: A Békebarlang felfedezése. Bp. 1953, Művelt Nép. 94 p. 25 t.

JAKUCS L.: Aggtelek és vidéke. Útikalauz. [Ill.] (Apródi Jenő, Bakonyi Kálmán stb.) Bp. 1957, Sport Kiadó. 317 p. 32 t. 1 térk.

(JAKUCS L.): Aggtelek. [Közreadja az] IBUSz. Bp. 1959, Közdok. 110 p. 1 t. A szöveg angol, német és szlovák nyelven is.

JAKUCS L.: Felfedező utakon a föld alatt. [Bev.] (Tamás Ferenc.) Bp. 1959, Gondolat. 253 p. 7 t.

JAKUCS L.: A mészkőhegyek születése. A TIT Földtan-geofizikai választmányának kiadása. Bp. 1960, 19 p.

JAKUCS L.: Charakteristika Madarskeho krasu. Jaskyna Baradla. = Droppa, Anton: Domica-Baradla. Bratislava, 1961, p. 104-127.

JAKUCS L.: Gefangen in der Baradla-Höhle. Forschungen in den unterirdischen Labyrinthen Ungarns. Leipzig, 1961, Brockhaus Verl. 299 p.

JAKUCS L.: Aggtelek és környéke. /Az Észak-borsodi karsztvidék/ utikalauza. [Közrem.] (Anton Droppa, Dénes György stb.) 2. átdolg. és bőv. kiad. Bp. 1961, Sport ^O Medicina. 358 p. 16 t. 1 térk., 2 térk. mell.

(JAKUCS L.): Az aggteleki Baradla cseppkőbarlang. Bp. [1961], IBUSz. 63 p., ill. /Ismerd meg hazádat!/

A barlangok világa. /Barlangjárók zsebkönyve./ (Szerk.) JAKUCS (L.), Kessler (Hubert). Bp. 1962, Sport - Medicina. 264 p. 21 t., ill. térk.

JAKUCS L.: A faggyúfáklyás expedíció. Bp. 1962, Sport. 147 p. 25 t., ill. térk.

JAKUCS L.: V podzemnom carsztve. (Földalatti börtönben.) Moszkva, Goszudarsztvennoje Izdatyelsztvo Geograficseszkoi Literaturü [Ford.: M. P. Ulrich]. 1963, 272 p.

JAKUCS L.: Cseppkőország mélyén. Bp. 1964, Móra Kiadó. 125 p. 16 t. /Búvár Könyvek 43./

Általános természeti földrajzi gyakorlatok. Szerk. JAKUCS L. Egységes jegyzet. Bp. 1967, Tankvk. 243 p. /Természettudományi Karok [Jegyzetei]./ Ua. még további hat változatlan kiadásban.

JAKUCS L.: A karsztok morfogenetikája. A karsztfejlődés varienciái. Bp. 1971, Akadémiai K. 310 p. /Földrajzi Monográfiák. 8./

JAKUCS L.: Aggtelek. ([Közread. a] Borsod-Abaúj-Zemplén megye Tanácsának Idegenforgalmi Hivatala.) [Miskolc], 1975, 161 p., ill.

(Dénes György -JAKUCS L. - Jakucs Pál): Aggteleki-karsztvidék. Utikalauz. Bp. 1975, Sport. 404 p. 20 t. 2 térk. mell.

JAKUCS L.: Morphogenetics of karst regions. (A karsztok morfogenetikája.) Variants of karst evolution. (Transl.: by B[álint] Balkay.) Bp. - Bristol, 1977, Akadémiai K. - Hilger. 283 p., ill.

JAKUCS L.: Morphogenetics of karst regions. (A karsztok morfogenetikája.) Variants of karst evolution. (Transl.: by B[álint] Balkay.) New York - Bp., (1977), Willey - Akadémiai K. 283 p., ill. /A Halsted Press book./

JAKUCS L.: Morfogenez karsztovüh oblasztej. Variantü évoljucii karszta. Perev. sz anglijszkogo Sz. Sz. Gorcsakovoj. [Bevezető tanulmányát írta: N. A. Gvozdetzkij.] Moszkva Bp. 1979, Progreszsz - Akadémiai K. 392 p.

(JAKUCS L.): Baradla cseppkőbarlang. [közr. a] Borsod Tourist Borsod-Abaúj-Zemplén megyei Idegenforgalmi Hivatal. [Miskolc], [1979], [36] p. (Magyar, német, orosz és szlovák nyelven.)

(JAKUCS L.): Magyarország nevezetes karsztjelenségei. Bp. 1979, TIT. 47 p., ill. /Földtudományi ismeretterjesztés./

Bevezetés a magyar őstörténet kutatásának forrásaiba. (Szerk. Hajdú P[éter], Kristó Gy[ula], Róna-Tas A[ndrás].) Írta és összeáll. a Szegedi Őstörténeti Munkaközösség. 4. [köt.]

Történeti természettudományok és térképi források. Szerk. Tardy János. (Lektorok: Fodor István, JAKUCS L.) Bp. 1982. Tankvk. 319 p. /József Attila Tudományegyetem Bölcsészettudományi Kar./

JAKUCS L.: Barlangjaink születése és halála. = Kordos László: Magyarország barlangjai. Bp. 1984, Gondolat. p. 27-38.

JAKUCS L.: Cseppkő, heliktit, montmorillonit. = Kordos László: Magyarország barlangjai. Bp. 1984, Gondolat. p. 38-50.

JAKUCS L.: Az aggteleki Baradla-Domica barlangrendszer. = Kordos László: Magyarország barlangjai. Bp. 1984, Gondolat. p. 88-109.

JAKUCS L.: A Békebarlang. = Kordos László: Magyarország barlangjai. Bp. 1984, Gondolat. p. 109-118.

JAKUCS L.: A megye földrajza. = Csongrád. (Bp.) 1985, p. 5-20. /Magyarország Megyéi./

JAKUCS L.: Csongrád megye homokterületeinek természetföldrajzi tájelemzése. = A szélerózió elleni védekezés lehetőségeinek és módszereinek feltárása Csongrád megye homokterületein. Szeged, 1989, p. 7-29. /A Magyar Tudományos Akadémia Szegedi Akadémiai Bizottságának Kiadványai./

JAKUCS L.: Általános természeti földrajz. 1. köt. A földrajzi burok kozmogén és endogén dinamikája. (Egyetemi jegyzet földrajz szakos tanárjelöltek részére. Lektorálta Szederkényi Tibor, Szatmáry Károly.) (Szeged), 1990, JATE K. IV, 522 p. /József Attila Tudományegyetem Természettudományi Kar./

JAKUCS L.: Szerelmetes barlangjaim. Szeged, 1991. Szerző. 443 p. 224 t.

JAKUCS L.: Általános természeti földrajz. 1. köt. A földrajzi burok kozmogén és endogén jelenségei. Földrajz szakos tanárjelöltek és szakgeográfusok részére. 2., bőv. kiad. (Lektorálta Szederkényi Tibor, Szatmáry Károly.) (Szeged), 1992, JATEPress. 359 p. /József Attila Tudományegyetem Természettudományi Kar./

JAKUCS L.: Természetföldrajz. 1. [köt.] A Föld belső erői. Szeged, 1993, Mozaik. 195 p. /Középiskolások kézikönyve./ Ua. 2. bőv. kiad. 1995.
JAKUCS L.: Szerelmetes barlangjaim. (Bp. 1993, Akadémiai K.) 315 p. 24 t.
JAKUCS L.: A karsztok sérülékenysége. = Aktuális problémák a földrajztanításban. Oktatási segédanyag. 1993, Magazin. p. 34-50.
JAKUCS L.: A magmatizmus és vulkanizmus földrajzi jelenségei. = Általános természetföldrajz. Fejezetek az általános természetföldrajz köréből. Szerk. Borsy Zoltán. Bp. 1993, Nemzeti Tankönyvkiadó. p. 85-115.
JAKUCS L. - Nagy G.-né: A Föld, amelyen élünk. 1. [köt.] Természetföldrajzi környezetünk tankönyve. Szeged, 1995, Mozaik. 168 p.
JAKUCS L. - Nagy G.-né: A Föld, amelyen élünk. 1. [köt.] Földrajz munkafüzet. Szeged, 1995, Mozaik. 96 p.
JAKUCS L.: Természetföldrajz. 2. [köt.] A Föld külső erői. Szeged, 1995, Mozaik. /Középiskolások kézikönyve./ Megjelenés alatt.

PUBLICATIONS, REPORTS:

JAKUCS L.: A hévforrásos barlangkeletkezés földtani alakulása. = Hidrológiai Közlöny, 1948. p. 53-58.
JAKUCS L.: Újabb hozzászólás a Budai-hegység hidrotermáinak eredetéhez. = Hidrológiai Közlöny, 1950. p. 233-235.
JAKUCS L.: Hozzászólás a Mátyáshegyi-Barlang kérdéseihez. = A Magyar Állami Földtani Intézet évi jelentése az 1941-1956. évekről. Bp. 1945-1959.
JAKUCS L.: A dolomitporlódás kérdése a Budai-hegységben. = Földtani Közlöny, 1950. p. 361-381.
JAKUCS L.: A Bükkhegység még feltáratlan, ismeretlen barlangrendszerei. = Földtani Közlöny, 1951. p. 200-201.
JAKUCS L.: Vízföldtani megfigyelések a Gömöri-karszton. = Földtani Közlöny, 1951. p. 464-467.
JAKUCS L.: A vízföldtani tudomány fejlődése a Szovjetunióban. = Földtani Közlöny, 1952. p. 215-218.
JAKUCS L.: Adatok néhány bükkhegységi karsztforrás ismeretéhez. = A Magyar Állami Földtani Intézet évi jelentése az 1941-1956. évekről. 1950. (Szerk. Gergelyffy Lászlóné.) Bp. 1953. Nehézip. Kiadó. p. 49-60.
JAKUCS L.: Jelentés az 1953. évi tavaszi karsztvízfestési vizsgálatokról. = A Magyar Állami Földtani Intézet évi jelentése az 1941-1956. évekről. Bp. 1945-1959.
JAKUCS L.: Néhány szó a Baradla és a Békebarlang kapcsolatáról. = Természet és Társadalom, 1954. p. 274-278.
JAKUCS L.: Adatok az Aggteleki-hegység és barlangjainak morfogenetikájához. = Földrajzi Közlemények, 1956. 1. sz. p. 25-38.
JAKUCS L.: Barlangkutatóink Csehszlovákiában. = Karszt- és Barlangkutatási Tájékoztató, 1956.
JAKUCS L.: A barlangi árvizekről. = Földrajzi Közlemények, 1956. 4. sz. p. 381-402.

JAKUCS L. - Markó László.: A barlangi légáramlás keletkezése. = Hidrológiai Közlöny, 1956. 4. sz. p. 314-316.
Szabó Pál Zoltán: A karszt, mint klimatikus morfológiai probléma. Hozzászólók: Kretzoi Miklós, JAKUCS L. stb. Pécs, 1957. /Dunántúli tudományos gyűjtemény 15. Ser. geographica 8./
JAKUCS L.: Jelentés a Baradla alsóbarlangjának feltárásáról. = Karszt és Barlangkutatási Tájékoztató, 1957. 1-6.
JAKUCS L.: A Békebarlang gyógyhatásvizsgálatának első eredményei. = Természettudományi Közlöny, 1959. 1. sz.
JAKUCS L.: Neue Methoden der Höhlenforschung in Ungarn und ihre Ergebnisse. = Die Höhle (Wien), 1959. Jg. 10. H. 4. p. 88-98.
JAKUCS L.: Százezer látogató Aggteleken. = Karszt és Barlangkutatási Tájékoztató, 1959.
JAKUCS L.: Feltűnő kutatási eredmények Aggteleken. = Karszt és Barlangkutatási Tájékoztató, 1959. p. 15-28.
JAKUCS L.: Az aggteleki lábnyomrejtély. = Borsodi Szemle, 1960.
JAKUCS L.: Általános karsztgenetikai, morfológiai és hidrográfiai problémák vizsgálata az Aggteleki-karszton. Kandidátusi értekezes. Jósvafő, 1960. 1. köt. p. 1-205., 2. köt. p. 206-356.
JAKUCS L.: Az aggteleki barlangok genetikája a komplex forrásvizsgálatok tükrében. = Karszt- és Barlangkutatás, 1959. 1. évf. p. 37-65.
JAKUCS L.: Nuovi metodi di studio e risultati delle ricerche nelle grotte d'Ungheria. = Rassegna Speleologica Italiana (Como), 1960. Anno 12. Fasc. 1. p. 3-10.
JAKUCS L.: Über die Förbung der Tropfsteine in den Höhlen. = Karszt- és Barlangkutatás, 1962. p. 21-47.
JAKUCS L.: Berechnung der Karstversickerungswerte im Aggteleker Karstgebiet. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1961-1964. Tom. 5. Fasc. 1-7. p. 17-30.
JAKUCS L.: Le grotte giganti dell' Ungheria. = Rassegna Speleologica Italiana (Como), 1962. Anno 14. Fasc. 3. p. 1-4.
JAKUCS L.: A jegesbarlangok képződése. = Földrajzi Zsebkönyv, 1963. 14. évf. p. 50-62.
JAKUCS L.: A barlangi cseppkövek szineződéséről. = Karszt és Barlangkutatási Tájékoztató, 1963. 7-8. sz. p. 123-135.
JAKUCS L.: Internationale Beitröge zur Karstmorphologie. [Zeitschrift für Geomorphologie, Supplementband 2., Göttingen, 1960. 107 p. 3 mell.] [Rec.] = Földrajzi Értesítő, 1963. 12. évf. 3. f. p. 444-445.
JAKUCS L.: Geomorfológiai problémák az Észak-borsodi Karsztvidéken. Dolinatípusok és terra rossa szintek. = Borsodi földrajzi évkönyv, Miskolc, 1964. p. 12-23. /Borsodi Szemle könyvtára 5./
JAKUCS L.: Die Friedenshöhle in Ungarn als klimatherapentischer Kurort fér Erkrankungen der Atmungsorgane. = Akten III. Intern. Kongress f. Speleologie. Bd. 4. Wien, 1965.

JAKUCS L.: Untersuchungen über den Dynamismus und Chemismus den Tropfsteinbildung. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1966. Tom. 6. Fasc. 1-4. p. 3-22.
Andó Mihály - JAKUCS L.: Békés megyei homok- és kavicselőfordulások. (Kéziratos szakvélemény tanulmány.) 1-2. köt. Szeged, 1966-1967. JATE. p. 1-40., 1-90.
JAKUCS L.: A barlangok az idegenforgalom szolgálatában. = Idegenforgalmi Kollokvium, 3. Budapest, 1966. nov. 22-24. [Rend.]: Országos Idegenforgalmi Hivatal. [Előadások.] [Bp. 1967], Panoráma.
JAKUCS L.: Eine neue Erklörung der Denudationsvorgönge und Morphogenetik der Karstlandschaften. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1967. Tom. 7. Fasc. 1-6. p. 3-42.
JAKUCS L. - Andó Mihály: A Dél-Tiszántúl természeti földrajzi tájértékelése. Kutatási összefoglaló jelentés az Országos Kőolaj- és Gázipari Trösztnek. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1967. 173 p.
JAKUCS L.: Offene Fragen der morphogenetischen Deutung nach Plateauniveaus des Karstformschatzes des Nord-Borsoder Karstes. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1968. Tom. 8. Fasc. 1-5. p. 3-15.
JAKUCS L.: Szempontok a karsztos tájak denudációs folyamatainak és morfogenetikájának értékeléséhez. (Contributions to the evaluation of the denudation processes and morphogenetics of karst landscapes.) = Földrajzi Értesítő, 1968. 17. évf. 1. f. p. 17-46.
JAKUCS L. - Andó Mihály: A Duna-Tisza köze déli részének természeti földrajzi tájértékelése. Kutatási összefoglaló jelentés az Országos Kőolaj- és Gázipari Trösztnek. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1968. JATE. 128 p.
JAKUCS L.: A karsztfejlődés varienciáinak genetikus rendszere. Akadémiai doktori értekezés. 1969. 493 p.
JAKUCS L.: Voraussetzungen für die Epirovarianz der Verkarstung. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1969. Tom. 9. Fasc. 1-5. p. 63-80.
JAKUCS L.: The morphogenetic problems observated in the karst dolines of Nord Borsod (Hungary) = Kárpát-Balkán Geomorf. Asszociáció 1969-es krakkói Karsztmorfológiai Szimpoziumának Actai. Krakow, 1969.
JAKUCS L.: Evaluacion del papel del clima en la morfologia de los carsos. = Simposium 30 Aniversario de la Sociedad Espeleológica de Cuba. La Habana 1970. (del 3 al 17 Noviembre de 1970.) Espeleológica y Carsológica, No. 7. pp. 76-80.
JAKUCS L.: A karsztfejlődés varienciáinak genetikus rendszere. Akadémiai doktori értekezés tézisei. Bp. 1970. [Tudományos Minősítő Bizottság.] 41 p.
JAKUCS L.: Kubai barlangokban. (In kubanischen Höhlen.) = Karszt és Barlang, 1970. 2. sz. p. 89-92.
JAKUCS L.: The role of climate in the quantitative and qualitative control of karstic corrosion. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1970. Tom. 10. Fasc. 1-8. p. 3-19.

JAKUCS L.: Saludo del delegado de la Academia de Ciencias de Hungria. = Simposium 30 Aniversario de la Sociedad Espeleológica de Cuba. La Habana, 1970. (del 3 al 17 Noviembre de 1970.) Espeleológica y Carsológica, No. 7. p. 34-35.
JAKUCS L. (munkatársakkal): A szénhidrogéntárolásra alkalmas karsztos horizontok és üregrendszerek általános kifejlődési törvényszerűségeinek nagylengyeli értékelése. Tanulmány az Országos Kőolaj- és Gázipari Trösztnek. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1970. 259 p.
JAKUCS L. (munkatársakkal): A Duna-Tisza köze északi részének természeti földrajzi tájértékelése. Kutatási összefoglaló jelentés az Országos Kőolaj- és Gázipari Trösztnek. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1970. 311 p.
*JAKUCS L.: Dynamische Unterschiede des Verkarstungsprozesses in den Mikroröumen. Szeged, 1971. JATE soksz. 58 p., ill. /International Geographical Union, European Regional Conference. Symposium on Karst-Morphogenesis. [Budapest], 1971./
JAKUCS L.: Regulatoren der Karstkorrosion durch Petrovarianz. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1971. Tom. 11. Fasc. 1-7. p. 3-26.
JAKUCS L.: Szempontok a dolomittérszinek karsztosodásának értelmezéséhez. (Beitröge zur Deutung der Verkarstung von Dolomitflöchen.) = Földrajzi Értesítő, 1971. 20. évf. 2. f. p. 89-98.
JAKUCS L: Magyarország nagyobbméretű természetes barlangrendszereinek vizsgálata a folyékony halmazállapotú szénhidrogének tározási lehetőségei szempontjából. Összefoglaló tanulmány az Országos Kőolaj- és Gázipari Trösztnek. Kézirat. Szeged, 1971. 263 p.
JAKUCS L.: Die Deutung der Karstkorrosion der in der Natur vorkommenden Kalkgesteine in der Geomorphologie unserer Zeit. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1972. Tom. 12. Fsc. 1-7. p. 3-36.
Balázs Dénes - JAKUCS L.: [Beszámoló az 1971. aug. 5-9. között Budapesten rendezett Karszt-morfogenetikai szimpóziumról.] = Földrajzi Közlemények, 1972. új folyam 20. (96.) köt. 2-3. sz. p. 250-252.
JAKUCS L.: Dr. Wagner Richárd. (1905. márc. 21 - 1972. pr. 1.) [Nekr.] = Földrajzi Közlemények, 1972. új folyam 20. (96.) köt. 4. sz. p. 351-353.
JAKUCS L.: Dr. Wagner Richárd. [Nekr.] = Szegedi Egyetem, 1972. 10. évf. 6. sz. p. 2.
JAKUCS L.: Differences of dynamism of karst-formation processes in micro-areas. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1973. Tom. 13. Fasc. 1-7. p. 3-35.
Symposium on Karst-Morphogenesis. International Geographical Union. European regional conference. Hungary, 1971. Papers. (Ed. by JAKUCS L. Publ. by the Faculty of Science at "Attila József" University.) (Szeged), 1973. (JATE Soksz.) 304 p.
JAKUCS L.: The karstic corrosion of naturally occurring limestones in the geomorphology of our age. = Symposium on Karst-Morphogenesis. International Geographical Union. European regional conference. [Budapest, 5-9. August, 1971.] Papers. (Publ.: Faculty of Science at Attila József University) (Szeged), 1973. p. 52-121.

JAKUCS L.: The role of climate in the quantitative and qualitative control of karstic corrosion. = Symposium on Karst-Morphogenesis. International Geographical Union. European regional conference. [Budapest, 5-9. August, 1971.] Papers. (Publ.: Faculty of Science at Attila József University) (Szeged), 1973. p. 122-152.

JAKUCS L.: Die Rolle des Klimas in der quantitativen und qualitativen Regelung der Karstkorrosion. = Petermanns Geographischen Mitteilungen, 1973. Jg. 117. p. 7-13.

JAKUCS L. (munkatársakkal): Környezetvédelem és szénhidrogéntermelés. Kutatási összefoglaló tanulmány az Országos Kőolaj- és Gázipari Trösztnek. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1. köt. 1972. 133 p., 2. köt.1973. 219 p.

JAKUCS L. (munkatársakkal): A magyarországi alsó Dunavölgy adottságainak természeti földrajzi vizsgálata. Kutatási összefoglaló jelentés a Városépítési Tudományos és Tervező Intézetnek (Budapest). Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1972. 287 p.

JAKUCS L. (munkatársakkal): A Dél-Dunavölgy domborzatának és felszínfejlődési tendenciáinak természeti földrajzi vizsgálata. Kutatási összefoglaló jelentés az Építésügyi és Városfejlesztési Minisztériumnak. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1973. 244 p.

JAKUCS L.: Effects of relief configuration and human intervention on the nature of the karst process. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1974. Tom. 14. Lib. 1. Fasc. 1-6. p. 3-13.

JAKUCS L. (munkatársakkal): A kalocsai és mohácsi körzet természetföldrajzi tájpotenciáljainak vizsgálata a távlati iparteleptési lehetőségek szempontjából. Kutatási összefoglaló tanulmány az Építésügyi és Városfejlesztési Minisztériumnak. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1974. 144 p.

JAKUCS L. (munkatársakkal): A KGST tagállamainak olaj és gáz nagyterületei és az olaj- és gázkutatás irányai ezeken a területeken. A kárpáti köztes medencék területe. Összefoglaló értékelő tanulmány a KGST Állandó Bizottságának. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1974. 198 p. Magyar és orosz nyelven.

JAKUCS L.: A Fekete-tenger és a Kaszpi-tó asztroblém eredete. (The astrobleme origin of the Black-sea and Caspian-sea.) = Földrajzi Értesítő, 1975. 24. évf. 4. f. p. 433-438. 2 t.

JAKUCS L.: Megemlékezés a Baradla-barlang 150 éves évfordulójáról. = Baradla 150. Nemzetközi konferencia. Budapest - Aggtelek, 1975. [augusztus] 26-29. (Rend. a Magyar Karszt- és Barlangkutató Társulat. [Előadások.] Szerk. Hazslinszky Tamás.) Bp. 1975.

JAKUCS L.: Questions of the oil-contamination of soil-water and agricultural soils in the Southern Part of the Hungarian Basin. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1975. Tom. 15. Fasc. 1-10. p. 3-33. 1 t.

JAKUCS L.: Astrobleme origin of the European Black Sea and the Caspian Sea. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1976. Tom. 16. Fasc. 1-12. p. 3-13.

JAKUCS L. - Mezősi G bor: Genetic problems of the huge gypsum caves of the Ukraine. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1976. Tom. 16. Fsc. 1-12. p. 15-38.
JAKUCS L. (munkatársakkal): Az Alföld gázos vízkútjai teréleti és mélységi előfordulási rendszerének kutatási eredményei. Kutatási összefoglaló tanulmány az Országos Vízügyi Hivatalnak. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1976. 179 p.
JAKUCS L.: Genetic types of the Hungarian karst. = Karszt és Barlang, 1977. Special issue. p. 3-18.
JAKUCS L.: Morfologicseszkie i évoljucionnüe tipü karsztov Vengrii. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1977. Tom. 17. p. 65-103.
JAKUCS L.: A természetföldrajz lehetőségei a Dél-Alföld energiabázisának felkutatásában. (The role of physical geography in the discovery of energy resources in the southern region of the Great Hungarian Plain.) = Alföldi tanulmányok, 1977. p. 9-42.
JAKUCS L. - Bárány Ilona - Mezősi Gábor: Problems of geomorphology in the light of the 13. International Geographical Congress. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1977. Tom. 17. p. 105-110.
JAKUCS L. - Mezősi Gábor: Genetic problems of the huge gypsum caves of the Ukraine. = Proceedings of the 7th International Speleological Congress. Sheffield, England, Sept. 1977. p. 248-251.
JAKUCS L. - Mezősi Gábor: Ukrajna óriás gipszbarlangjainak genetikai problémái. (Genetic problems of the huge gypsum caves of the Ukraine.) = Földrajzi Értesítő, 1977. 26. évf. 1. f. p. 119-137.
JAKUCS L.: Physical-geographical and geological aspects of the exploration of the hydrocarbon reserves of the South Hungarian Plain. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1978. Tom. 18. p. 91-105. 18 t.
JAKUCS L. - Bárány Ilona - Mezősi Gábor: Beszámolók a Nemzetközi Földrajzi Unió 23. kongresszusa egyes szekcióinak, szimpóziumainak és módszertani szemináriumainak munkájáról. (1. szekció: Geomorfológia, paleogeográfia. Geomorfológiai eredmények.) = Földrajzi Közlemények, 1977. [1978.] 25. köt. 4. sz. p. 345-348.
JAKUCS L.: A magyarországi karsztok fejlődéstörténeti típusai. (Geneticseszkie tipü vengerszkih karsztov.) = Karszt és Barlang, 1977. 1-2. [1979.] p. 16.
JAKUCS L. (munkatársakkal): A szatellit-felvételek földtudományi interpretálás nak nemzetközi tapasztalatai, hazai lehetőségei és metodikái. Kutatási összefoglaló jelentés a Központi Földtani Hivatalnak. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1978. 278 p.
Crna-Gora tanulmányút. 1978. május 5-14. Programszervező és szakvezető: JAKUCS L. [Kiad. a] JATE Természeti Földrajzi Tanszék. Szeged, [1978.] 23 lev.
JAKUCS L.: Asztroblémek kimutatása műholdfelvételek segítségével. (Demonstration of astroblemes with the help of satellite exposures.) = Földrajzi Közlemények, 1979. 27. (103.) köt. 1-3. sz. p. 28-35. 3 t.

JAKUCS L.: Detection of astroblemes with the help of satellite photographs. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1979. Tom. 19. p. 83-94.
JAKUCS L.: A földrajz tárgya, funkciója, tagolódása és tudományközi helyzete. = Földrajztanítás, 1979. 22. évf. 2. sz. p. 45-50.
JAKUCS L.: A szegedi 1. téglagyár agyagbányájának részletes kutatási összefoglaló földtani jelentése. Szakértői jelentés a Békés Megyei Tégla- és Cserépipari Vállalatnak. Kézirat. Békéscsaba, 1979. 136 p. 9 t. 4 térk.
JAKUCS L. (munkatársakkal): A Duna-Tisza közéről készült LANDSAT felvételek földtudományi értékelése. Kutatási összefoglaló jelentés a Központi Földtani Hivatalnak. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1979. 178 p.
JAKUCS L.: A karszt biológiai produktum! (Karsts are biological products.) = Földrajzi Közlemények, 1980. 28. (104.) köt. 4. sz. p. 331-344. 2 t.
JAKUCS L.: Karszt - produkt biologicseszkih proceszszov. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1980. Tom. 20. p. 3-18. 1 t.
JAKUCS L.: Karsztmorfológia és barlanggenetika. - Barlangfelfedezések 1945-1961 között. = Hetvenéves a szervezett magyar karszt- és barlangkutatás. 1910-1980. [Szerk. Hazslinszky Tamás.] Bp. 1980, MKBT. p. 20-28., 67-78.
JAKUCS L. (munkatársakkal): A Dél-Tiszántúl területéről készült LANDSAT felvételek földtudományi értékelése. Kutatási összefoglaló jelentés a Központi Földtani Hivatalnak. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1980. 159 p. 1 t.
JAKUCS L. (munkatársakkal): A magyarországi tájak alföldi környezetökológiájának változási trendjei. Kutatási összefoglaló tanulmány az Erdészeti Tudományos Intézetnek (Budapest). Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1980. 211 p.
A Jugoszlávia karsztvidékei c. speciálkollégium szlovéniai-horvátországi tanulmányútjának programja. 1980. szept. 6-14. Programszervező és szakvezető: JAKUCS L. [Kiad.a] JATE Természeti Földrajzi Tanszék. Szeged, 1980. 23 lev.
JAKUCS L.: Der Karst ist ein biologisches Produkt. = Der Höhlenforscher, 1981. Jg. 13. H. 4. p. 51-57.
JAKUCS L.: A Dél-Alföld az ország településhálózatában, a fejlesztés eszköz- és érdekeltségi rendszere c. békéscsabai tudományos konferencia anyagai. Hozzászólás. Békéscsaba, 1981. p. 80-81.
JAKUCS L. (munkatársakkal): A Tiszai-Alföld északi feléről készült LANDSAT felvételek földtudományi értékelése. Kutatási összefoglaló jelentés a Központi Földtani Hivatalnak. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1981. 179 p. 1 t.
JAKUCS L. (munkatársakkal): Magyarázó és dokumentációs jegyzék Móraváros 1:10000-es geomorfológiai térképéhez. Kutatási összefoglaló jelentés a Magyar Állami Földtani Intézetnek. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1981.
JAKUCS L.: Az árvizek gyakoriságának okai és annak tényezői a Tisza vízrenszerében. (Ursachen für die Höufigkeit der überschwemmungen und deren Faktoren im Flusssystem der Theiss.) = Földrajzi Közlemények, 1982. új folyam 30. köt. 3. sz. p. 212-235.

JAKUCS L.: A Duna-Tisza köze műholdas földtudományi kutatása. (Geonomical research in the Danube-Tisza Interfluve with satellite images.) = Alföldi tanulmányok, 1982. p. 87-128.

JAKUCS L.: Megnyitó beszéd a Magyar Földrajzi Társaság 34. Vándorgyűlésén, Szegeden, 1981. június 27-én. = Földrajzi Közlemények, 1982. új folyam 30. köt. 3. sz. p. 203-205.

JAKUCS L. - Andó Mihály - Bárány Ilona - Fehér József - Mezősi Gábor - Tóth Imre: Geoscientific interpretation of material relating to the region between the Danube and the Tisza in Hungary, obtained by remote sensing from the LANDSAT satellites. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1982. Tom. 22. p. 3-101.

JAKUCS L. (munkatársakkal): A Kis-Alföldről készült LANDSAT felvételek földtudományi értékelése. Kutatási összefoglaló jelentés a Központi Földtani Hivatalnak. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1982. 120 p. 1 t.

JAKUCS L. (munkatársakkal): Magyarázó Móraváros 1:10000-es műszaki állapot térképéhez. Kutatási összefoglaló jelentés a Magyar Állami Földtani Intézetnek. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1982. 61 p.

JAKUCS L. (munkatársakkal): Magyarázó és dokumentációs jegyzék Kiskundorozsma 1:10000-es geomorfológiai térképéhez. Kutatási összefoglaló jelentés a Magyar Állami Földtani Intézetnek. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1982. 50 p.

JAKUCS L.: Karszt - produkt biologicseszkih proceszszov. = European Regional Conference on Speleology, Sofia, Bulgaria, 22-28 September, 1980. Proceedings Vol. 2. Sofia, 1983. p. 157-164.

JAKUCS L. - Kevei[né] Bárány Ilona - Mezősi Gábor: A modern interpretation of karst corrosion. - A karsztkorrózió korszerű értelmezése. = Földrajzi Közlemények, 1983. 31. köt. 3-4. sz. 207-217. p.

Bárány Ilona - JAKUCS L.: Szempontok a karsztfelszíni formák rendszerezéséhez, különös tekintettel a dolinák típusaira. = Földrajzi Közlemények, 1983.

JAKUCS L.: Geological analysis of the Kis-Alföld based on satelite-photos. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1983. Tom. 23. p. 119-158. 3 t.

JAKUCS L.: Zárójelentés a K-14 célprogram keretében végzett Természetföldrajzi folyamatok befolyásolásának a tájenergiák fejlődését módosító távlati visszahatásai c. kutatási téma befejezéséről. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1983. 83 p.

JAKUCS L. (munkatársakkal): Építőipari nyersanyagok kutatása Békés, Csongrád és Bács-Kiskun megyében. Kutatási összefoglaló jelentés a Központi Földtani Hivatalnak. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1983. 223 p.

JAKUCS L.: Basic principles in the application of geomorphology in hydrocarbon research. = Geographical essays in Hungary. (Contribution to the International Geographical Congress, Paris Alpes, 1984.) Bp. 1984. p. 179-185. /Theory - Methodology - Practice. Elmélet - Módszer - Gyakorlat. 29./

JAKUCS L.: Egyes karsztbarlangok légzéstherápiai hatékonyságának oki tényezői. = VII. Nemzetközi Szpeleotherápiai Szimpózium (Keszthely - Tapolca, 1982. nov. 2-6.) Actai. [Kiad. a] Magyar Karszt- és Barlangkutató Társaság. Bp. 1984. p. 63-84.
JAKUCS L.: A természeti környezet átformálásának folyamata az Alföldön. = Az Alföld gazdaságföldrajzi kutatásának eredményei és további feladatai. (1. A plenáris ülés előadásai.) [Kiad. az] MTA FKI Alföldi Csoportja. Békéscsaba, 1984. p. 18-36.
JAKUCS L.: A Kisalföld műholdas vizsgálata. = Földrajzi Közlemények, 1984. 32. köt. 3. sz. p. 217-254.
JAKUCS L.: Physical geographical picture of Csongrád County. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1984. Tom. 24. p. 89-103.
JAKUCS L. - Bárány Ilona: Oecological factors playing part in Karstdenudation dynamism for different geographical zones. = 24th Congress of the International Geographical Union. Paris, 1984. Th. 1. 80.
JAKUCS L.: Megnyitó [a Prinz Gyula születésének 100. évfordulója alkalmából rendezett emlékülésen.] = Földrajzi Közlemények, 1984. 32. köt. 1. sz. p. 2-4.
JAKUCS L.: Megkezdődött a cseppkőbarlangok pusztulásának korszaka? = Természet Világa, 1984. 115. évf. 3. sz. 124-125. p.
JAKUCS L.: Válasz [Maucha László hozzászólásához a Megjegyzések a Megkezdődőtt a cseppkőbarlangok pusztulásának korszaka? c. cikkhez.] = Természet Világa, 1984. 115. 12. sz. p. 569.
Bárány Ilona - JAKUCS L.: Szempontok a karsztok felszínformáinak rendszerezéséhez, különös tekintettel a dolinák típusaira. (On the systematization of karst landforms with special regard to doline types.) = Földrajzi Értesítő, 1984. 33. évf. 3. füz. 259-265. p.
JAKUCS L. (munkatársakkal): A nagylengyeli szénhidrogéntározó blokkok karsztgenetikai modellje, s a kőolajkészletek pontosítására eszközölt kísérleti-módszertani vizsgálatok. Kutatási összefoglaló jelentés a Kőolajipari és Földgázbányászati Vállalatnak (Nagykanizsa). Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1984. 176 p.
JAKUCS L.: A nagylengyeli kőolajtározó, illetve az ahhoz hasonló üregrendszerek hidraulikai szempontból jellemző formái és méretei. Irányelvek a karsztos üregtározó terek kísérleti modelljének elkészítéséhez és a vele végzendő kísérletek lefolytatási módozataihoz. Szakvélemény. Szeged, 1984. 31 p.
JAKUCS L.: Előzetes jelentés a nagylengyeli kőolajmező modelljének pontosítása érdekében végzett vizsgálatokról. Kőolaj- és Földgázbányászati Vállalatnak (Nagykanizsa). Kézirat. Szeged, 1984. 27 p.
JAKUCS L.: A nagylengyeli kőolajmező geológiai modelljének karsztgenetikai vizsgálata. Szakértői jelentés a Kőolaj- és Földgázbányászati Vállalatnak (Nagykanizsa). Kézirat. Szeged, 1984. 18 p.
Karsztjelenségek és kutatási feladatok Jugoszláviában c. tanulmányút programja (1984. szept. 1-16.) Programszervező és szakvezető: JAKUCS L. [Kiad. a] JATE Természeti Földrajzi Tanszék. Szeged, 1984. 23 lev.
JAKUCS L.: Reflexiók az Aggteleki Nemzeti Parkhoz. = Természet Világa, 1985. 116. évf. 6. sz. p. 264-268.

JAKUCS L.: Factors responsible for the effectiveness of certain karst caves in respiration therapy. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1985. Tom. 25. p. 61-72.

JAKUCS L. (munkatársakkal): A savas esők és a karsztjelenségek. Beszámoló a kutatási eredményekről az Országos Környezet- és Természetvédelmi Hivatalnak. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1985. 132 p. 52 t.

JAKUCS L.: Changes in water level regimes in karst-denudation regions, influenced by mining activity, in the various limestone and dolomite reservoirs. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1986. Tom. 26. p. 27-51.

JAKUCS L.: Traces of effects of acid rain /sedimentation/ in the re-dissolution of cave dripstones. = IGU/Study Group on Man's Impact in Karst Areas, Palma de Mallorca, Meeting-August 1986. p. 7.

JAKUCS L.: Transformation of the physical environment in the Great Hungarian Plain, 1945-1985. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1986. Tom. 26. p. 3-25.

JAKUCS L.: A savas esők (ülepedések) hatásának nyomai a barlangi cseppkövek visszaoldódásában. = Karszt és Barlang, 1986. 1. sz. p. 15-22.

JAKUCS L.: Traces of effects of acid rain /sedimentation/ in the re-dissolution of cave dripstones. = ENDINS, 1987. No. 13. p. 49-57.

JAKUCS L.: Az újtípusú cseppkődegradációra vonatkozó legújabb kutatási eredmények. Összefoglalás. (The latest investigational results concerning the dripstone-degradation of a new type.) = Oktatási intézmények karszt- és barlangkutató tevékenységének 2. országos tudományos konferenciája. Szombathely, 1987. p. 53-54.

JAKUCS L. - [Keveiné] Bárány Ilona: Ecological factors playing part in karst denudation dynamism for different geographical zones. = Processus et measure de l'érosion sous la direction d'Alain Godard et Anders Rapp. 25e Congres International de Geographie, Paris, 1984. Paris, 1987. p. 387-392.

JAKUCS L. - Mezősi Gábor: Relationship between doline types and geomorphological surfaces in Hungary. = Pleistocene environment in Hungary. Contribution of the INQUA Hungarian National Comittee to the XIIth INQUA Congress, Ottawa, 1987. Ed by Márton Pécsi. Bp. 1987. p. 163-170. /[Magyar Tudományos Akadémia Földrajztudományi Kutató Intézet.] Elmélet - módszer - gyakorlat. 42./

JAKUCS L.: The effect of acidic atmosphere pollution upon stalagmites in karstic cave-system. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1987. Tom. 27. p. 3-37.

JAKUCS L.: Hevesi Attila kandidátusi védése. = Karszt és Barlang, 1987. 1-2. f. p. 57-59.

JAKUCS L. (munkatársakkal): Építőipari nyersanyagok kutatása Nógrád, Heves, Borsod-Abaúj-Zemplén és Szabolcs-Szatmár megyék síksági területein. Kutatási összefoglaló jelentés a Központi Földtani Hivatalnak. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1987. 152 p. 4 térk.

JAKUCS L.: Vallomások a kollégiumról. = A Debreceni Református Kollégium Gimnáziumának jubileumi (1538-1988) évkönyve. Debrecen, 1988. p. 255-258.

JAKUCS L.: Physico-geographical and climatological landscape analysis in the sand areas of Csongrád county with special regard to prevention of wind erosion. = Acta Universitatis Szegediensis. Acta Geographica. Szeged, 1990. Tom. 28-30. p. 3-30.

JAKUCS L. (munkatársakkal): Építőipari nyersanyagok kutatása a Kis-Alföldön. Kutatási összefoglaló jelentés a Központi Földtani Hivatalnak. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1989. 105 p. 3 térk.

JAKUCS L. (munkatársakkal): A Nagy- és Kis-Alföld építőipari nyersanyagkutatás nak eredményei. Összefoglaló tudományos értékelés az 1983-90-es években a Központi Földtani Hivatal részére elvégzett kutatómunkákról. Kézirat. (JATE Természeti Földrajzi Tanszék). Szeged, 1990. 84 p. 4 térk.

JATE karsztexpedíció Jugoszláviában. 1990. aug. 25-szept. 9. A program tervezete. Programszervező és szakvezető: JAKUCS L. [Kiad. a] JATE Természeti Földrajzi Tanszék. Szeged, 1990. 9 lev.

JAKUCS L.: Bérczi Szaniszló: Kristályoktól bolygótestekig. [Ism.] = Földrajzi Közl. 1991. 39. köt. 3-4. sz. p. 228-229.

JAKUCS L.: Előszó Kordos László "Barlangkutatás" c. kiadványához. = Barlangos, 1991. 1 sz. p. 32.

JAKUCS L. - Mezősi Gábor: A podóliai gipszbarlangok genetikájáról. = Karszt és Barlang, 1991. 1-2. sz. p. 45-52.

JAKUCS L.: Reflexiók egy nosztalgikus visszaemlékezéshez. = Barlangos, 1992. 8. sz. p. 54-55.

JAKUCS L.: A Kossuth-barlang még ismeretlen, feltáratlan részei. = Kossuth-emléknapok (Aggtelek - Jósvafő, 1992. szept. 18-20.) Emlékülés előadásai. [Kiad. a] Magyar Karszt- és Barlangkutató Társaság. Bp. 1992. p. 105-114.

JAKUCS L.: Aggtelek. Karsztmorfológiai tanulmányút 1993. szept. 1-5. Programfüzet és szemelvényes szakmai tájékoztató. [Kiad. a] JATE Természeti Földrajzi Tanszék. Szeged, 1993. p. 21.

JAKUCS L.: A karsztokról 34 tételben. = Természet Világa, 1993. 124. évf. 5. sz. p. 210-214.

JAKUCS L.: Földrajzi világképünk megújulása. = A földrajz tanítása (Szeged), 1993. 1. évf. 1. sz. p. 4-6.

JAKUCS L.: Környezetromlási gondok az Alföldön. 1. = A földrajz tanítása (Szeged), 1993. 1. évf. 3. sz. p. 8-13.

JAKUCS L.: Környezetromlási gondok az Alföldön. 2. = A földrajz tanítása (Szeged), 1993. 1. évf. 4. sz. p. 3-6.

JAKUCS L.: A földrajzoktatás három feladata. = A földrajz tanítása (Szeged), 1993. 1. évf. 2. sz. p. 3-6.

JAKUCS L.: Impakt jelenségek a Föld felszínén. = A földrajz tanítása (Szeged), 1994. 2. évf. 3. sz. p. 3-10.

JAKUCS L.: A Budai-hegység hidrotermális karsztja. = Földrajzi Értesítő, 1994. 43. évf. 3-4. f. p. 235-246.

POPULAR LITERATURE:

JAKUCS L.: Ott, ahol az aszfalt terem. = Ifjúság és élet, 1942. 18. évf. 3. sz. p. 30-31.
JAKUCS L.: Az ember nem is gondolná! Természetrajzi érdekességek. = Ifjúság és élet, 1942. 17. évf. 11. sz. p. 132.
JAKUCS L.: Aranybánya. (Naplórészlet Nagybányáról.) = Ifjúság és élet, 1942. 17. évf. 17. sz.
JAKUCS L.: Erdélyi sóhegy. = Ifjúság és élet, 1943. 18. évf. 15. sz. p. 172.
JAKUCS L.: A barlangok keletkezése. = Természettudomány, 1947. p. 54-60.
JAKUCS L.: Hogyan alakult ki az aggteleki barlangrendszer? = Élet és Tudomány, 1951. febr.
JAKUCS L.: Forrásvédelem, egészségvédelem, természetvédelem. = Természet és Technika, 1953. 3. sz. p. 165-168.
JAKUCS L.: A Pénzpataki-cseppkőbarlang felfedezése. = Élet és Tudomány, 1954. szept. 15. p. 464-468.
JAKUCS L.: Utak építése a Baradlában. = Idegenforgalmi Tájékoztató, 1954. márc.
JAKUCS L.: A Pénzpataki-cseppkőbarlang felfedezése. = Kerek egy esztendő. [évkönyv gyermekeknek, versekkel, elbeszélésekkel.] 1955. (Szerk. Domokos Mátyás, Enzci Endre. ill. Kozsvári György, Muray Róbert stb.) Bp. 1955. Ifj. Kiadó. p. 275-278.
JAKUCS L.: A barlangkutatás új irányai. = Természetjárás, 1955. okt.
JAKUCS L.: Árvíz a hegyek alatt. = Élet és Tudomány, 1955. dec.
JAKUCS L.: Aggtelek új barlangcsodái. = Képes Magyarország, 1956. jan.
JAKUCS L.: Barlangvasutat kér a Baradla. = Képes Magyarország, 1956. ápr.
JAKUCS L.: The stalactite cave of Aggtelek. = Hungarian Magazine (Budapest), 1956.
JAKUCS L.: Felfedezőúton az aggteleki Alsóbarlangban. = Élet és Tudomány, 1957.
JAKUCS L.: Búvárruhás felfedezőút a Békebarlangban. = Élet és Tudomány, 1958. márc.
JAKUCS L.: Jugoszlávia barlangvilágában. = Természetjárás, 1958.
JAKUCS L.: Nemzetközi barlangkutató kongresszus. = Természetjárás, 1958.
JAKUCS L.: Kisvasutat Aggteleknek! = Figyelő, 1958. máj. 27.
JAKUCS L.: Építsünk barlangvasutat a Baradlában! = Borsodi Műszaki Élet, 1958.
JAKUCS L.: Az aggteleki lábnyomrejtély. = Természetjárás, 1959. dec.
JAKUCS L.: Az Aggteleki-cseppkőbarlang. = Élet és Tudomány, 1960. jan.
JAKUCS L.: A barlangi szifonok kutatásáról. = Élet és Tudomány, 1960. jan.
JAKUCS L.: Die Riesenhöhles Ungarns. = Urania (Leipzig), 1961. mai Jg. 19. p. 187-189. 1 t.
JAKUCS L.: A Meteor-barlang. = Képes Magyarország, 1963. 3. p. 5-6.
JAKUCS L.: 17 napig tartott a szanki gázkitörés. = Élet és Tudomány, 1965. p. 503-507.
JAKUCS L.: A Föld alatti campingezés. = Természettudományi Közlöny, 1966. 10. (97.) évf. 7. sz. p. 325-327.
JAKUCS L.: La gas-erupcio ce vilago Szank. Trad. Tibor Ujklaky-Nagy. = Hungara Vivo, 1966. jaro 6. 2. p. 24-25.
JAKUCS L.: Kuba trópusi karsztjain. = Föld és ég, 1972. 7. évf. 1. sz. p. 3-6.
JAKUCS L.: Búvópatakok nyomában 1. = Élet és Tudomány, 1973. 28. évf. 38. sz. p. 1785-1789.

JAKUCS L.: Különleges barlangóriások. = Föld és ég, 1974. 9. évf. 2. sz. p. 34-37.
JAKUCS L.: Felfedező úton a világ legnagyobb gipszbarlangjában. = Fiúk évkönyve 1976. Bp. 1976. Móra K. p. 252-257.
JAKUCS L.: Gipszbarlangok útvesztőiben. = Élet és Tudomány, 1978. 33. évf. 13. sz. p. 399-402.
JAKUCS L.: Évmilliók testamentuma. Hazánk különleges barlangjai és karsztjai. = Búvár, 1989. 44. évf. 8. sz. p. 2-13.
JAKUCS L.: Hogyan keletkeznek a barlangok? = Élet és Tudomány, 1989. 44. évf. 32. sz. p. 995-997.
JAKUCS L.: Megvédhető-e a dunántúli karsztvíz? = Élet és Tudomány, 1989. 44. évf. 24. sz. p. 739-741.
JAKUCS L.: A világhírű Baradla. = Búvár, 1989. 44. évf. p. 18-20.
JAKUCS L.: Mennyire függünk a Naptól? = Élet és Tudomány, 1989. 44. évf. 17. sz. p. 515-517.
JAKUCS L.: A csodákban hinni kell! = Délsziget (Hatvan), 1994. 28. sz. p. 15-20.

CONTENTS